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## **Solar Power from Space: European Strategy in the Light of Sustainable Development**

### **Phase 1: Earth and Spaced based power generation systems**

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# 1 Summary

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## 1.1 Introduction

A large amount of world energy production is currently based on non-renewable sources such as oil, gas and coal. Global warming and restricted fossil energy sources force a strong demand for another climate compatible energy supply. Beside wind, biomass, water energy, etc., solar energy is a promising solution. However, it suffers alternating supply between day and night, winter and summer and at cloudy skies. To overcome this problem and guarantee a steady power supply, electricity generation in space and transmission to earth has been proposed in the late sixties. Huge lightweight photovoltaic panels are to be placed in low or geostationary earth orbit and the collected energy transmitted to a receiver on earth via microwave or laser beam. Power can be sent thus directly to where it is needed. Several studies yet have been done to develop realizable concepts. Due to high transportation costs into space and lacking technical maturity, these concepts have not been realized so far. With ongoing technology improvement, this may change and energy supply from space become of interest in the future.

However, space systems have to compete with the yet existing, established and well known terrestrial solutions as photovoltaic and solar thermal power plants. Checking viability and meaningfulness of Solar Power Satellites in economical and technical aspects has been the main aim of this study, concentrating on the electricity supply for Europe. Especially the cases of constant base load and the remaining load have been investigated in detail for several power levels from below 1 GW to full supply. Within a combined space-terrestrial scenario a 24-hour supply with a real load curve has been assumed to get an impression of an optimized realistic situation. Results are levelised electricity costs (LEC) and energy payback time (EPT).

## 1.2 Basic Assumptions

### Scenario situation

Annual irradiation sums in the supply zone (West and Central Europe, zones B-U in Figure 1) show values from 900 kWh/m<sup>2</sup> Global Horizontal Irradiation (GHI) in northern Europe to maximal 2000 kWh/m<sup>2</sup> in southern European countries (or 700 kWh/m<sup>2</sup> to 2200 kWh/m<sup>2</sup> Direct Normal Irradiation, DNI). Population density in Europe is high and land widely used. Solar power plants therefore have to compete with agriculture or forestry, raising the price for renewable energy. In the so called sun belt in North Africa the irradiation with GHI values from 2000 to 2400 kWh/m<sup>2</sup> or DNI from 2300 to 3000 kWh/m<sup>2</sup> is significantly higher. Land there is widely available as huge areas are unused in the Sahara desert (Figure 2). With little land available, the whole energy supply can hardly be generated in Europe. A suitable alternative is North Africa (zones A1 to A3 in Figure 1). The energy is transferred to Europe by HV-DC lines (T1-T3 in Figure 1). North Africa offers also a high annual coverage of clear skies. This might especially be important when energy transmission through space systems is applied.

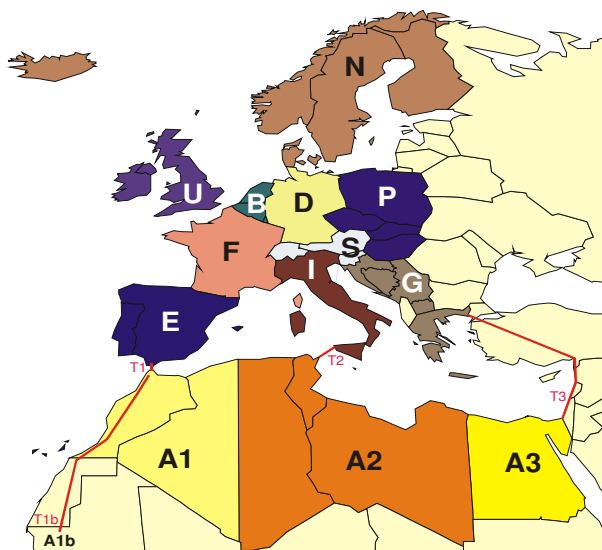


Figure 1. Definition of supply and generation zones in Europe and North Africa

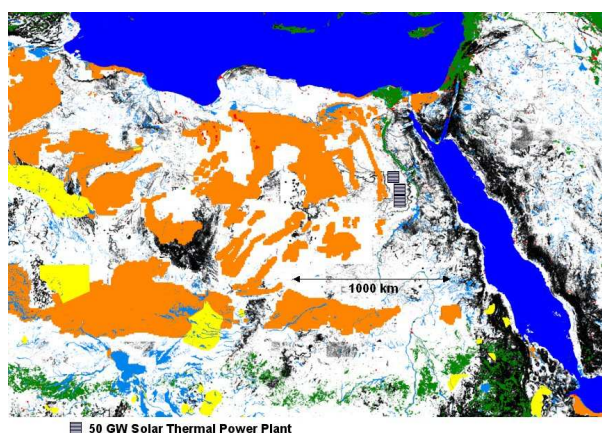


Figure 2. Availability of land in Northeast Africa: white area is suitable for the construction of solar power plants. Base load full supply (150 GW) of solar thermal needs only a small portion of available land

The actually necessary power amount for the supply zone has been estimated along interpolated hourly load values from the UCTE and CENTREL net of the year 2000. For the N and U zones with the net operators NORDEL and UKTSOA/TSOI we got only the annual consumption, so the UTCE/CENTREL load curve has been scaled by 136% to cover the whole supply zone. The load curve for the future scenario has been estimated assuming a mean annual growth rate of 1.5% until 2030. The minimal, average and maximal demand load of the total supply zone B-U of the years 2000 and the assumed demand loads for 2030 is presented in Table 1.

Table 1. Demand loads of supply zones B-U

| Year | Minimum in GW | Average in GW | Maximum in GW | Consumption in TWh/a |
|------|---------------|---------------|---------------|----------------------|
| 2000 | 196           | 324           | 436           | 2,842                |
| 2030 | 309           | 512           | 689           | 4,489                |

The minimal load value occurring during one year within this study means base load with 8760 constant full load hours per year. The exceeding power corresponds to remaining load with base load subtracted from the real load curves (as illustrated in Figure 3).

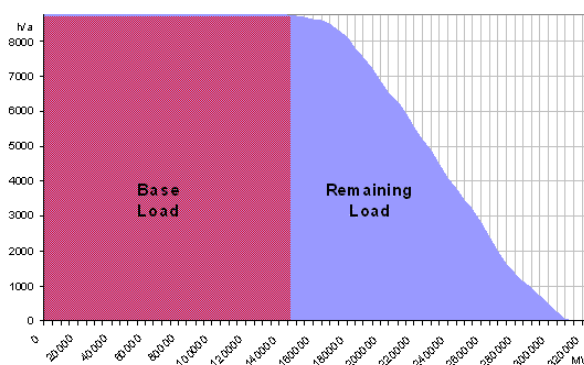


Figure 3. Definition of base load and remaining load: full load hours in dependence on the demand power

As 41.8 GW of base load is hydropower, which will remain in operation anyhow, 150 GW of base load remains for 2000. Taking into consideration the development of wind power in the recent 8 years, its installed power has been increasing between 32 and 46% per year to 23 GW in 2002. Continuing with a moderate growth rate of 10 to 15% per year would lead to a complete coverage of the base load demand in 2030. Therefore, scenarios with different power levels from 500 MW over some multi-GW until a full power supply at no more than 150 GW have been examined.

The calculation of the terrestrial power generation was done with the simulation tool “greenius” for power plants of 1 GW, using hourly, site-specific irradiation data. The results have been scaled afterwards for the different power levels, respecting storage needs.

### Overview of space-based technologies

Dr. Peter Glaser introduced the SPS concept in the 1960s. However, at that time the required technology was not available. DOE / NASA showed the feasibility of the concepts in studies performed in the 1970s (5 GW SPS in GEO). In general, the conceptual approach was as follows:

|                     | <b>Baseline Solution</b> | <b>Back-up Solution</b> |
|---------------------|--------------------------|-------------------------|
| Power Generation:   | Photovoltaic             | Solar-dynamic           |
| Power Transmission: | $\mu$ -wave @ 2.35 GHz   | Laser                   |
| Re-conversion:      | Rectenna                 | Thermodynamic           |

The use of microwave power transmission involves a number of problems:

- o Large transmission antenna (1.3 km radius), large ground rectenna (15 km radius)
- o Diffraction limited long distance  $\mu$ -wave WPT; intensity limits (23 mW/cm<sup>2</sup>)
- o Long time exposure limits of biological material to  $\mu$ -wave (side lobes and spikes)
- o Safe, clean, affordable access to space

The conclusions drawn out of these former investigations were:

- o DOE/NASA 1970s studies showed the feasibility, but first step was found too expensive.
- o This was confirmed by follow-on studies (ESA and Germany, eg. European Sail Tower Concept)
- o The NASA Fresh Look Study (1995 / 1997) stated, that the access to space is still too expensive
- o The NASA SERT Programme (1998 - ) was to conduct preliminary strategic research investigation and to re-evaluate the SPS concepts

Due to their overall impact on the SPS system mass and cost the most critical technologies are:

- o Solar Power Generation (stretched lens array, rainbow array, thin film PV, quantum dot, Brayton Cycle Solar Dynamic)
- o Power Management and Distribution (DC-DC conversion, DC-AC-DC conversion LT/HT super conductor)
- o Wireless Power Transmission (laser type, magnetron, klystron)
- o High effective thermal control
- o Large, lightweight self-deployable structures and dynamic structure control
- o In-orbit transportation (reusable/semi-reusable systems)
- o Power re-conversion on earth (PV, solar thermal)
- o High efficient long distance power transmission on ground (HVDC)

The beaming or wireless transmission of power relies either on microwave or laser technology. In this study both ways has been treated, but major emphasis is put on laser systems. Two basic concepts exist:

*Microwave - wavelength ca. 1 cm*

The issues are here:

- o Short transmission distance or large apertures or higher frequency
- o 2.35 GHz with excellent efficiency state of the art
- o Higher frequencies (35 GHz to 60 GHz) at a reduced efficiency

*Laser: wavelength ca. 1 micro m*

The issues are here:

- o Good beam focussing over very long distance, but low efficiency

- o Thermal stability of receptor limits core intensity (waste heat)
- o Beam jitter and potential damage at high concentration

The reasoning to prefer laser power transmission technology, in the frame of this study, is mainly to avoid the drawbacks of microwave transmission, despite the relatively high microwave efficiency and the technology development status, achieved up today. Drawbacks in microwave transmissions are the occurrence of side lobes/spikes, the difficult control in failure cases and the much higher mass and sizing requirements of the transmitting elements compared to the laser system (up to factor of 50).

Summarizing these actual arguments of laser versus microwaves the following could be stated:

- o Microwave systems are relatively efficient and provide less attenuation by atmospheric effect
- o R/F spectral constraints on MW side-lobes and grating-lobes imposed by the ITU result in design and filtering requirements; this leads to reduced efficiency and larger, more costly systems
- o Laser systems allow a smooth transition from conventional power to SPS, and offer more useful space applications and open up new architecture solutions
- o Electronic laser beam steering probably required to keep mechanical complexity and mass within acceptable limits
- o Laser and microwave systems have different design drivers, and due to their potential, laser based systems deserve a comparable consideration
- o In terms of launch, transportation and assembly efforts microwave systems are more complex and costly compared to laser systems (big transmitter antenna)

### **Specification of selected space-based technologies**

For the *space generation system* the technology presented in Figure 4 has been chosen. For one SPS unit 110.7 km<sup>2</sup> of thin film PV cells are placed in geostationary orbit (GEO) with an additionally concentrator of the same size, generating nearly constantly 53 GW of the incoming 275 GW of direct sunlight. The energy is transmitted to ground via laser beam at a receiver of 68.9 km<sup>2</sup>. This receiver consists of PV cells of a similar type as for the terrestrial PV technology (Table 3), which finally insert 7.9 GW of electricity (plus additional terrestrial irradiation) into the grid. Together with the terrestrial irradiation this unit delivers 10 GW of constant power assuming that the daily course of the terrestrial irradiation is buffered by pumped hydroelectricity. Up to three space units are supposed to send the beam to one ground receiver, which then delivers constantly 25 GW. Cloudy locations have to be avoided for the ground receiver, as clouds will extinguish laser light. The costs of the space unit are listed in Table 2.

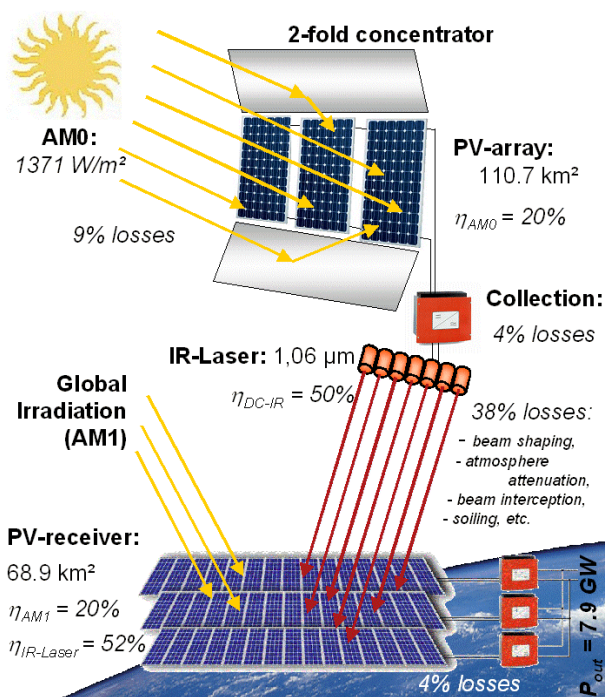


Figure 4. Technology of the space generation system

Table 2. Costs of the space system

| Space system costs                          | Initial                        | Progress rate |
|---------------------------------------------|--------------------------------|---------------|
| PV                                          | 4500 €/kW <sub>p</sub>         | 0.8 / 0.92    |
| Conc.&Control                               | 11.5 bill. €/SPS               | 0.8 / 0.92    |
| Laser                                       | 8.8 bill. €/SPS                | 0.8           |
| Transportation                              | 55.3 bill. €/SPS<br>(530 €/kg) | 0.9           |
| Financing                                   |                                | 6.7%          |
| Space system lifetime                       |                                | 30 years      |
| Operation&Maintenance costs (of investment) |                                | 0.6%          |

### Specifications of terrestrial technologies

At ground either photovoltaic or solar thermal power plants have been used for electric power generation: The technological data of the *PV system* is listed in Table 3.



Table 3. Technology data of the terrestrial PV system

|                                            | 2000        | 2020/2030               |
|--------------------------------------------|-------------|-------------------------|
| PV cell                                    | cryst. Si   | 3 <sup>rd</sup> gen. PV |
| $\eta_{\text{module}}$                     | 14.2%       | 15%                     |
| $\eta_{\text{inverter}}$                   | 96%         | 98%                     |
| Losses (soiling, etc.)                     | 10%         | 7%                      |
| Initial costs                              | 4,500 €/kWp | 4,500 €/kWp             |
| Progress ratios                            | 0.82 / 0.92 | 0.8 / 0.9               |
| Glob. Installed capacity / GW <sub>p</sub> | 2           | 100                     |
| PV system lifetime                         | 25 a        | 25 a                    |
| O&M costs (of investment)                  | 2.2%        | 2.7%                    |

At the present scenario crystalline silicon PV cells are used. The cost reduction ratio is 0.82 (for now installed 2 GW<sub>p</sub>) until half of price is reached and will be 0.92 then, depending on the globally installed power (Figure 5).

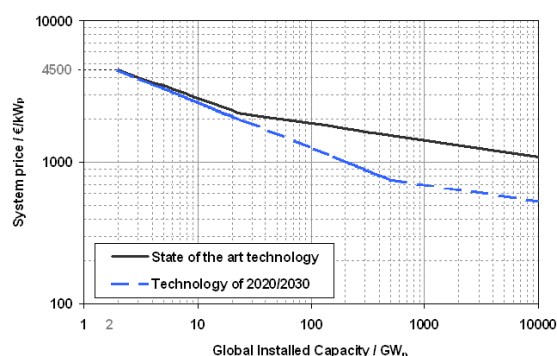


Figure 5. PV installation costs in dependence on global installed capacity  
(=initial+2×scenario installation)

The installation within this scenario is assumed to invoke the same amount of additional installation in the world. Until 2020/2030 a technology change will take place to 3<sup>rd</sup> generation PV cells like e.g. multi junction solar cells with costs as illustrated also in Figure 5. For a maximal power output with only slight variation throughout the year, PV panel inclination will be changed manually two times per year in spring and autumn for 10° inclination in summer and 60° in winter.

The reference *Solar Thermal Power Plant* consists of a Eurotrough-2 collector, thermal oil as fluid, a Rankine steam turbine cycle and two storage tanks with molten salt (Figure 6). Further technical data is listed in Table 4.

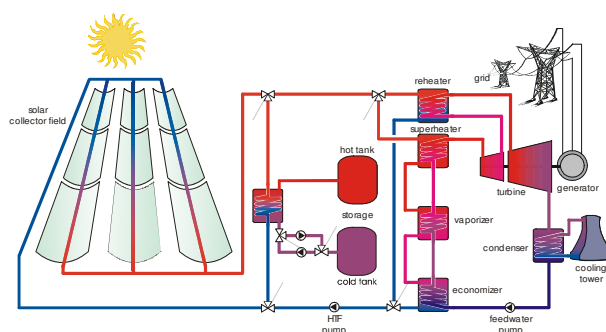


Figure 6. Solar Thermal Trough Power Plant with storage

Table 4. Technology data of the Solar Thermal system.

|                                        | 2000                   | 2020/2030                   |
|----------------------------------------|------------------------|-----------------------------|
| Solar thermal system                   | Eurotrough-2           | Improved ST                 |
| $\eta_{\text{collector}}$              | 66%                    | Overall efficiency:<br>>20% |
| $\eta_{\text{power block}}$            | 39%                    |                             |
| Losses (soiling, etc.)                 | 6%                     |                             |
| Initial costs:                         |                        |                             |
| Collector:                             | 225 €/m <sup>2</sup>   | 225 €/m <sup>2</sup>        |
| Power block:                           | 800 €/kW <sub>el</sub> | 800 €/kW <sub>el</sub>      |
| Storage:                               | 30 €/kWh <sub>th</sub> | 30 €/kWh <sub>th</sub>      |
| Progress ratios                        | 0.88 / 0.96            | 0.88 / 0.96                 |
| Glob. inst. capacity / km <sup>2</sup> | 2.3                    | 100                         |
| ST system lifetime                     | 25 a                   | 25 a                        |
| O&M costs (of invest.)                 | 2.9%                   | 2.9%                        |

The future Solar Thermal power plant will be an advanced trough system (e.g. direct steam generation) with improved components and efficiencies, or a high-efficiency solar thermal power tower using a combined cycle. Cost depression will change at a global installation of 500 km<sup>2</sup> from 0.88 to 0.96. In 2020/30 the installation within the scenario will initialize 1.5 times the installation throughout the world.

First simulation runs for the *storage system* showed that there is no need for seasonal storage. As e.g. land in east Egypt between the Nile and the Red Sea is mountainous at high altitude, pumped hydroelectric storage is used.

Table 5. Technical data of the pumped hydroelectric storage system

| Pumped hydroelectric storage     | 2000 | 2020/2030 |
|----------------------------------|------|-----------|
| $\eta_{\text{charge-discharge}}$ | 75%  | 85%       |
| Storage power costs / €/kW       | 700  | 600       |
| Storage capacity costs / €/kWh   | 14   | 12        |
| System lifetime                  | 40 a | 40 a      |
| O&M costs / €/kWh                | 6    | 4         |

Produced electricity exceeding the storage capacity is assumed to be sold for a dumping price of 0.02 €/kWh in 2000 or 0.025 €/kWh in the future scenario. As hydrogen storage has low efficiency (see Table 6) it has only be considered for comparison purposes in the combined scenario (see section on combined systems).

Table 6. Technical data of the hydrogen storage

| Hydrogen storage: pressure vessel storage |                         |
|-------------------------------------------|-------------------------|
| $\eta_{\text{electrolyzer}}$              | 65%                     |
| $\eta_{\text{Fuel cell/CCGT}}$            | 55%                     |
| Electrolyser investment                   | 500 €/kWh <sub>H2</sub> |
| Electrolyser O&M                          | 1.5%                    |
| Pressure vessel costs                     | 1.92 mill. €/vessel     |
| Fuel Cell/CCGT costs                      | 500 €/kW <sub>el</sub>  |
| Fuel Cell/CCGT O&M costs                  | 0.01 €/kW <sub>el</sub> |
| System lifetime                           | 30 a                    |

*Transmission lines:* The generated electricity is transported from the power plant/receiver to the near storage system by High Voltage AC lines and from the storage by one of the paths T1-T3 (see Figure 1) to the centre of the next supply zone via HV DC lines. Among the single supply zones electricity is exchanged via DC lines, within one zone distributed by AC lines. The technical data of the transmission lines is listed in Table 7.

Table 7. Technical data of the transmission lines

| Transmission lines              | 2000                  | 2020/2030             |
|---------------------------------|-----------------------|-----------------------|
| HV DC double dipole line        | 600 kV                | 800 kV                |
| Capacity / GW                   | 5                     | 6.5                   |
| Losses/1000 km                  | 3.3%                  | 2.5%                  |
| Losses/station                  | 0.7%                  | 0.5%                  |
| Power line costs                | 300 million €/1000 km | 300 million €/1000 km |
| Costs of AC/DC-station          | 350 million €/station | 350 million €/station |
| Progress ratio                  | 0.96                  | 0.96                  |
| Start length                    | 10,000 km             | 10,000 km             |
| System lifetime                 | 25 a                  | 25 a                  |
| O&M costs                       | 1%                    | 1%                    |
| HV AC double lines              | 1,150 kV              | 1,150 kV              |
| Losses/1000 km                  | 4.4%                  | 4.4%                  |
| Line costs / mill. €/1000 km/GW | 200                   | 140                   |
| Progress ratio                  | 0.96                  | 0.96                  |
| Starting point                  | 10,000 km GW          | 10,000 km GW          |
| System lifetime                 | 25 a                  | 25 a                  |
| O&M costs (of investment)       | 1%                    | 1%                    |

## Financing

The basic economic values are calculated along the following equations 1-3:

Annuity  $a$ :

$$a = ir / (1 - (1 + ir)^{-n}) \quad (1)$$

with discount rate  $ir$  and system lifetime  $n$ .

Present value ( $PV$ ):

$$PV = c_{Inv} + c_{O\&M} \cdot ((1 + ir)^n - 1) / (ir \cdot (1 + ir)^n) \quad (2)$$

with investment costs  $c_{Inv}$  and annual operation and maintenance costs  $c_{O\&M}$ .

Levelised electricity costs ( $LEC$ ):

$$LEC = PV \cdot a / E_a \quad (3)$$

with the annual demand  $E_a$ .

### Energy payback time

The energy payback time (*EPT*) of a system is the time in which an energy system produces the same amount of energy as consumed for its production, operation and dismantling. The energy needed to produce the system consists of energy needed to produce the materials, transportation energy, energy needed for installation and system set-up. The *EPT* is calculated along:

$$EPT = CED_c / (E_{net} / g - CED_0) \quad (4)$$

with the cumulated energy demand for construction  $CED_c$ , the yearly produced net energy  $E_{net}$ , the utilization grade  $g$  of primary energy source for electricity generation and the annual energy expense for maintenance  $CED_0$ . The *EPT* of 2020/2030 has been calculated respecting a probable energy mix and utilization grade  $g$  in 2020/2030.

## 1.3 Results

From the big variety of data, which define a certain scenario, only the most important are presented here. The levelised electricity costs are determined along the simulation results of the expected annual generation of electricity and at a discount rate for the investors of 6%.

### Base Load

Base load is a constant demand for 8760 hours per year. Table 8 and Table 9 show the installed capacities of the generation system (PV or Solar Thermal) as well as the necessary capacity and power of the pumped hydroelectric storage system with technology standards of today for several demand power levels.

Table 8. Base load scenario of today PV

| Demand               | GW              | 0.5   | 5     | 10    | 100   | 150   |
|----------------------|-----------------|-------|-------|-------|-------|-------|
| PV cap.              | GW <sub>p</sub> | 3     | 33    | 65    | 653   | 997   |
| Stor. power          | GW <sub>p</sub> | 2.1   | 23.7  | 42.5  | 425   | 651   |
| Stor. cap.           | GWh             | 180   | 820   | 200   | 3000  | 3500  |
| LEC                  | €/kWh           | 0.284 | 0.207 | 0.180 | 0.146 | 0.142 |
| EPT                  | month           | 28.7  | 32.4  | 31.9  | 32.0  | 32.6  |
| <b>LEC-breakdown</b> |                 |       |       |       |       |       |
| Generation           |                 | 58%   | 52%   | 51%   | 48%   | 47%   |
| Storage&Dumping      |                 | 36%   | 40%   | 35%   | 40%   | 38%   |
| Transmission         |                 | 6%    | 8%    | 13%   | 12%   | 15%   |

Table 9. Base load scenario of today Solar Thermal

| Demand               | GW               | 0.5   | 5     | 10    | 100   | 150   |
|----------------------|------------------|-------|-------|-------|-------|-------|
| SoTh cap.            | GW <sub>el</sub> | 0.75  | 7.7   | 15.5  | 150   | 220   |
| Stor. power          | GW <sub>p</sub>  | 0.5   | 5     | 10    | 32    | 47    |
| Stor. cap.           | GWh              | 62    | 620   | 680   | 255   | 370   |
| LEC                  | €/kWh            | 0.136 | 0.095 | 0.083 | 0.060 | 0.057 |
| EPT                  | month            | 8.4   | 8.9   | 9.4   | 9.4   | 9.2   |
| <b>LEC-breakdown</b> |                  |       |       |       |       |       |
| Generation           |                  | 68%   | 64%   | 66%   | 67%   | 65%   |
| Storage&Dumping      |                  | 23%   | 29%   | 23%   | 12%   | 15%   |
| Transmission         |                  | 10%   | 7%    | 11%   | 21%   | 20%   |

As the transmission line T1 in Figure 1 between Spain and Morocco yet exists, the smaller power levels primarily have been calculated for generation zone A1 respectively A1b. As for power levels over 10 GW new transmission lines have to be build anyhow, electricity generation has been shifted to zone A3 because the annual irradiation sum there is significantly higher and also the daily course of irradiation shows less breakdowns caused by cloudy skies. Shifting to zone A3 explains the unsteadiness in the storage capacity.

Necessary capacities for electricity generation and the storage system are generally significantly higher for photovoltaics than for solar thermal power plants. Solar thermal power plants with its molten salt tanks have an efficient storage system yet integrated and are therefore capable to deliver a constant power level as long as its capacity lasts, whereas photovoltaics is generating electricity only during daytime. Electricity for the night hours has to be produced during daytime and stored by external storage systems.

The comparison on LEC and EPT show the high price and the expensive fabrication process of today's PV cells. Whereas electricity from Solar Thermal Power Plants costs from 0.14 to 0.06 € per kWh and has an EPT of under 10 month, the LEC of photovoltaics lies between 0.28 and 0.14 €/kWh with an EPT between 28 and 33 months.

Looking on improved technologies of 2020/2030, also solar power from space has to be considered, as it hopefully may be mature and available then. With its nearly constant output it is well suited for base load. Table 10 shows the number of SPS units in space and on ground, the installed capacities and the respective LEC and EPT for several power levels.

Table 10. Base load provided by the space system

| Demand                   | GW              | 10    | 25    | 50    | 100    | 150    |
|--------------------------|-----------------|-------|-------|-------|--------|--------|
| SPS units (space/ground) |                 | 1 / 1 | 3 / 1 | 6 / 2 | 12 / 4 | 18 / 6 |
| Space PV cap.            | GW <sub>p</sub> | 22.1  | 66.4  | 133   | 266    | 399    |
| Ground PV cap.           | GW <sub>p</sub> | 8.5   | 8.5   | 17    | 33.9   | 51     |
| Stor. capacity           | GWh             | 200   | 500   | 1000  | 2000   |        |
| LEC (530 €/kg)           | €/kWh           | 0.26  | 0.166 | 0.137 | 0.113  | 0.10   |
| EPT                      | month           | 4.2   | 3.7   | 3.7   | 3.7    |        |

The PV capacity here with its continuous generation is around half as high as for the terrestrial PV power plant. The LEC of the space system shows values of 0.26 € per kWh for smaller power levels and goes down to 0.10 €/kWh for 150 GW, further decreasing for even higher power levels (see Figure 7). These power levels will only be necessary for a worldwide power supply. The EPT of the space system with around 4 month is very short.

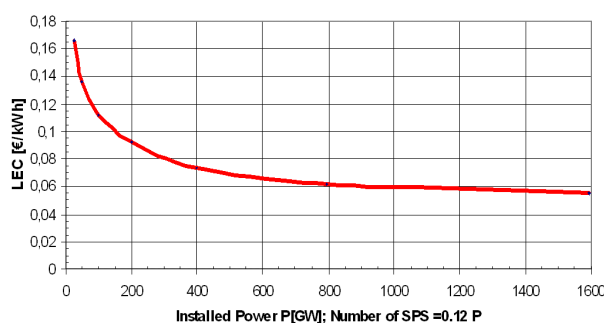


Figure 7. Levelised Electricity Costs of the space system

The capacities, storage power levels as well as LEC, its breakdown and EPT of the future terrestrial power plants are listed in Table 11 for PV and for Solar Thermal Power Plants in Table 12. Compared to the technologies of today, the necessary capacities and/or power levels will slightly decrease. The LEC and EPT values of the PV power plant however show significantly lower values of 0.12 to 0.07 €/kWh with around 8 months of Energy Payback Time. This is mainly due to the new technology. For the Solar Thermal Power Plants the LEC of the future scenario will be in the range of 0.05 to 0.09 €/kWh. EPT will be slightly below that of PV between 7 and 8 months. Regarding the breakdown of LEC for Solar Thermal Power Plants the biggest fraction belongs to the generation of electricity. For the PV power plant storage and dumping is about in the same range as generation because generation only takes place during daytime. The expenses for bringing the electricity to the supply zones is gaining importance with higher power levels.

Table 11. Base load of future PV

| Demand               | GW              | 0.5   | 5     | 10    | 100   | 150   |
|----------------------|-----------------|-------|-------|-------|-------|-------|
| PV cap.              | GW <sub>p</sub> | 3     | 30    | 55    | 553   | 846   |
| Stor. power          | GW <sub>p</sub> | 2.25  | 21.9  | 36.9  | 369   | 567   |
| Stor. cap.           | GWh             | 60    | 700   | 230   | 3000  | 3500  |
| LEC                  | €/kWh           | 0.123 | 0.115 | 0.087 | 0.068 | 0.066 |
| EPT                  | month           | 8.2   | 9.2   | 8.2   | 8.3   | 8.5   |
| <b>LEC-breakdown</b> |                 |       |       |       |       |       |
| Generation           |                 | 49%   | 40%   | 53%   | 46%   | 44%   |
| Storage&Dumping      |                 | 43%   | 50%   | 34%   | 39%   | 41%   |
| Transmission         |                 | 8%    | 10%   | 14%   | 15%   | 15%   |

Table 12. Base load of future Solar Thermal

| Demand               | GW               | 0.5   | 5     | 10    | 100   | 150   |
|----------------------|------------------|-------|-------|-------|-------|-------|
| SoTh cap.            | GW <sub>el</sub> | 0.73  | 7.5   | 15.1  | 138   | 208   |
| Stor. power          | GW <sub>p</sub>  | 0.5   | 5     | 10    | 32    | 48    |
| Stor. cap.           | GWh              | 70    | 605   | 530   | 255   | 375   |
| LEC                  | €/kWh            | 0.095 | 0.080 | 0.071 | 0.051 | 0.050 |
| EPT                  | month            | 6.8   | 7.4   | 8.0   | 7.3   | 7.4   |
| <b>LEC-breakdown</b> |                  |       |       |       |       |       |
| Generation           |                  | 65%   | 65%   | 69%   | 71%   | 70%   |
| Storage&Dumping      |                  | 26%   | 28%   | 20%   | 12%   | 12%   |
| Transmission         |                  | 9%    | 7%    | 12%   | 18%   | 18%   |

### Remaining Load

Remaining load denotes all power exceeding the lowest power level occurring once within a complete year. In contrary to base load its value is permanently changing with high values during the day and the evening and low values during the night. With that permanently change following this load curve with conventional power plants is a harder constraint. Thus the price for remaining load or peak load is usually higher. This is also true for PV power plants (see Table 13), where the LEC with 0.24 to 0.17 €/kWh as well as EPT with 38 to 41 month is about 20% higher for remaining load than for base load. Necessary storage capacity and power are even nearly doubling for high demand loads.



Table 13. Remaining load of today PV

| Demand               | GW               | 5     | 10    | 100   | 150   |
|----------------------|------------------|-------|-------|-------|-------|
| SoTh cap.            | GW <sub>el</sub> | 39    | 77    | 876   | 1243  |
| Stor. power          | GW <sub>p</sub>  | 29    | 57    | 613   | 920   |
| Stor. cap.           | GWh              | 380   | 890   | 4000  | 6000  |
| LEC                  | €/kWh            | 0.235 | 0.219 | 0.180 | 0.173 |
| EPT                  | month            | 38.2  | 37.7  | 40.5  | 40.5  |
| <b>LEC-breakdown</b> |                  |       |       |       |       |
| Generation           |                  | 40%   | 40%   | 35%   | 35%   |
| Storage&Dumping      |                  | 44%   | 45%   | 50%   | 50%   |
| Transmission         |                  | 15%   | 15%   | 15%   | 15%   |

Table 14. Remaining load of today Solar Thermal

| Demand                 | GW               | 5     | 10    | 100   | 150   |
|------------------------|------------------|-------|-------|-------|-------|
| SolarThermal cap.      | GW <sub>el</sub> | 11    | 22    | 224   | 336   |
| LEC                    | €/kWh            | 0.081 | 0.070 | 0.058 | 0.057 |
| EPT                    | month            | 12.3  | 12.3  | 12.3  | 12.3  |
| <b>LEC-breakdown</b>   |                  |       |       |       |       |
| Generation             |                  | 54%   | 56%   | 57%   | 57%   |
| Transmission & Dumping |                  | 46%   | 44%   | 43%   | 43%   |

The EPT of Solar Thermal Power Plants is also increasing about 30% to 12 months whereas contrarily LEC is slightly decreasing for remaining load to about 0.08 to 0.06 €/kWh (Table 14). The different behaviour of the Levelised Electricity Costs of PV respectively Solar Thermal originates from the higher storage demand for PV whereas at Solar Thermal Power Plants storage could be done completely within this plant. Additional pumped hydroelectric storage is not necessary.

The step to future scenarios of remaining load shows a very similar characteristic as for base load: The necessary capacities and power levels to be installed can be reduced by around 15 to 20% for PV (Table 15) and by about 5 to 10% for Solar Thermal (Table 16). The LEC and EPT of PV is going down significantly by a factor 2 for LEC and a factor 4 for EPT due to the technology change and also by notable 25% for LEC as well as EPT of Solar Thermal.

Table 15. Remaining load of future PV

| Demand               | GW              | 5     | 10    | 100   | 150   |
|----------------------|-----------------|-------|-------|-------|-------|
| PV capacity          | GW <sub>p</sub> | 33    | 67    | 704   | 1056  |
| Storage power        | GW <sub>p</sub> | 25    | 51    | 543   | 814   |
| Storage capacity     | GWh             | 410   | 665   | 4000  | 6000  |
| LEC                  | €/kWh           | 0.117 | 0.108 | 0.082 | 0.080 |
| EPT                  | month           | 10.1  | 9.9   | 10.4  | 10.5  |
| <b>LEC-breakdown</b> |                 |       |       |       |       |
| Generation           |                 | 40%   | 38%   | 30%   | 30%   |
| Storage & Dumping    |                 | 44%   | 46%   | 53%   | 54%   |
| Transmission         |                 | 16%   | 16%   | 17%   | 17%   |

Table 16. Remaining load of future Solar Thermal

| Demand                 | GW               | 5     | 10    | 100   | 150   |
|------------------------|------------------|-------|-------|-------|-------|
| SolarThermal cap.      | GW <sub>el</sub> | 11    | 22    | 216   | 324   |
| LEC                    | €/kWh            | 0.060 | 0.056 | 0.047 | 0.046 |
| EPT                    | month            | 11.9  | 9.9   | 10.0  | 10.0  |
| <b>LEC-breakdown</b>   |                  |       |       |       |       |
| Generation             |                  | 63%   | 64%   | 66%   | 67%   |
| Transmission & Dumping |                  | 38%   | 37%   | 34%   | 33%   |

## Combined Systems

For investigation of a more realistic scenario, the space and terrestrial systems have been combined to cover the power supply of a real load curve. The steady electricity supply of the space system is foreseen to deliver base load whereas the terrestrial system with its daily fluctuation is suited well for covering remaining load. Thus the need for storage is supposed to be minimized. As terrestrial system only photovoltaics has been considered for not mixing different technologies. In reality a further advantage of this solution is that installation of PV can be started yet with an optional add-on of the space system afterwards as illustrated in Phase 2 of Figure 8.

However, the design of the ground PV will differ depending on its use as a receiver either for a laser beam from a fix position or for capturing the maximal annual amount of global irradiation with the permanently varying solar angle. Thus spacing and inclination of the PV panels have to be optimized. The following four cases of combined scenarios have been investigated in detail:

- S-1: Ground receiver optimized for laser beam, additional terrestrial PV optimized for solar irradiation, pumped hydroelectric storage,
- S-2: PV as in S-1, hydrogen pressure vessel storage,
- S-3: PV on ground completely optimized for laser beam, pumped hydroelectric storage,

S-4: PV on ground completely optimized for solar irradiation (for provisional terrestrial set-up acc. To Figure 8), pumped hydroelectric storage.

For each of the four cases the whole combination range between a complete supply from SPS (without additional terrestrial PV: “SPS only”) and complete supply from terrestrial PV (without SPS) has been calculated. Thereby for a given number of SPS the terrestrial PV capacity as well as storage capacity have been optimized to yield the lowest LEC. The detailed numbers are presented in Table 17 to Table 20.

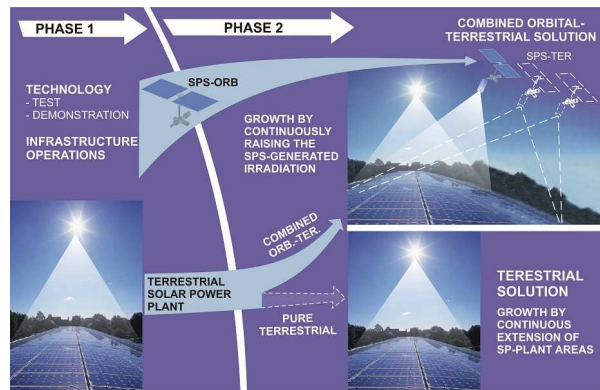


Figure 8. Set-up of a combined space-terrestrial power plant

The results for transportation costs of 530 €/kg (ground to GEO) are graphically illustrated in Figure 9 as the LEC of the four cases in dependence on the combination ratio: SPS only on the left side to terrestrial PV only on the right side.

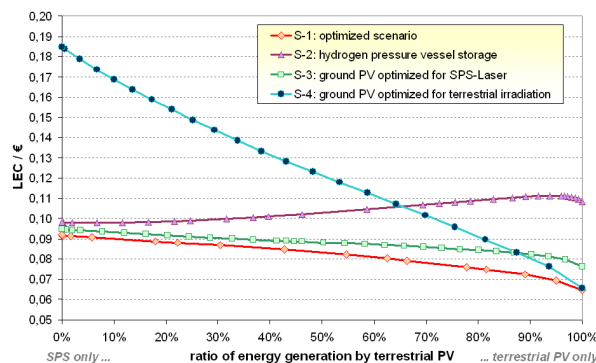


Figure 9. Levelised electricity costs of the combined space-terrestrial scenarios in dependence on the combination ratio for transportation costs of 530 €/kg

An expected optimal combination level space and terrestrial systems for the investigated cases cannot be found. Depending on the storage system or the design of the ground PV either pure SPS or pure terrestrial supply is the cheapest solution. The overall lowest electricity costs with 0.065 €/kWh are reached within the S-1 scenario for pure terrestrial electricity supply. The LEC is steadily rising with augmenting SPS ratio to 0.092 €/kWh for space supply only. A design of the whole ground PV

optimized for the laser beam as in S-3 yields slightly higher values especially compared to the higher terrestrial ratios but still resulting in pure terrestrial PV as the cheapest solution. The shift to the less efficient and therefore more expensive hydrogen storage (S-2) turns the result to the contrary: the cheapest solution then is the supply by the space system only. However, levelised electricity costs are 0.098 €/kWh increasing to 0.111 €/kWh in the 90% and going down again to 0.108 € for pure terrestrial supply. For the provisional set-up of the terrestrial system and later add-on of the space system along S-4, a high portion of the laser energy would be wasted due to higher spacing between the single PV module rows. Therefore the LEC is steeply rising to 0.185 €/kWh for pure SPS supply. This scenario is not very realistic as the necessary portion of the terrestrial PV would be redesigned as a laser beam receiver.

The costs for the transportation of the Solar Power Satellites from the earth to the geostationary orbit (GEO) have a strong influence on the LEC. This is shown for two levels of transportation costs from ground to GEO for the cases S-1 and S-2 in Table 17 and Table 18 here for pure space supply the LEC is raising even more steeply to 0.28 respectively 0.30 €/kWh for five times the transportation costs as assumed so far. So a strong reduction of the present transportation costs is required to make SPS competitive.

Table 17. Results of the combined scenario S-1

| Terrestrial ratio |                 | 0%           | 30%          | 66%          | 100%         |
|-------------------|-----------------|--------------|--------------|--------------|--------------|
| Number of SPS     |                 | 77           | 54           | 27           | 0            |
| Space PV cap.     | GW <sub>p</sub> | 1705         | 1196         | 598          | 0            |
| Ground PV cap.    | GW <sub>p</sub> | 221          | 153          | 76           | 0            |
| Terrest. PV cap.  | GW <sub>p</sub> | 0            | 737          | 1658         | 2621         |
| Storage capacity  | GWh             | 7309         | 9433         | 11310        | 12475        |
| LEC (530 €/kg)    | €/kWh           | <b>0.092</b> | <b>0.087</b> | <b>0.079</b> | <b>0.065</b> |
| LEC (2650 €/kg)   | €/kWh           | 0.284        | 0.229        | 0.158        | 0.065        |

Table 18. Results of the combined scenario S-2

| Terrestrial ratio |                   | 0%           | 30%          | 66%          | 100%         |
|-------------------|-------------------|--------------|--------------|--------------|--------------|
| Number of SPS     |                   | 83           | 63           | 36           | 0            |
| Space PV cap.     | GW <sub>p</sub>   | 1838         | 1395         | 797          | 0            |
| Ground PV cap.    | GW <sub>p</sub>   | 238          | 178          | 102          | 0            |
| Terrest. PV cap.  | GW <sub>p</sub>   | 0            | 910          | 2531         | 4844         |
| Storage capacity  | GWh <sub>H2</sub> | 9069         | 13455        | 16811        | 19503        |
| LEC (530 €/kg)    | €/kWh             | <b>0.098</b> | <b>0.100</b> | <b>0.107</b> | <b>0.108</b> |
| LEC (2650 €/kg)   | €/kWh             | 0.303        | 0.262        | 0.208        | 0.108        |

Table 19. Results of the combined scenario S-3

| Terrestrial ratio     |                 | 0%           | 30%          | 66%          | 100%         |
|-----------------------|-----------------|--------------|--------------|--------------|--------------|
| Number of SPS         |                 | 78           | 54           | 30           | 0            |
| Space PV cap.         | GW <sub>p</sub> | 1727         | 1196         | 664          | 0            |
| Ground PV cap.        | GW <sub>p</sub> | 221          | 153          | 85           | 0            |
| Terrest. PV cap.      | GW <sub>p</sub> | 0            | 918          | 2064         | 3478         |
| Storage capacity      | GWh             | 15434        | 12649        | 8807         | 13549        |
| <b>LEC (530 €/kg)</b> | <b>€/kWh</b>    | <b>0.095</b> | <b>0.090</b> | <b>0.086</b> | <b>0.077</b> |

Table 20. Results of the combined scenario S-4

| Terrestrial ratio     |                 | 0%           | 30%          | 66%          | 100%         |
|-----------------------|-----------------|--------------|--------------|--------------|--------------|
| Number of SPS         |                 | 191          | 108          | 54           | 0            |
| Space PV cap.         | GW <sub>p</sub> | 4229         | 2391         | 1196         | 0            |
| Ground PV cap.        | GW <sub>p</sub> | 543          | 305          | 153          | 0            |
| Terrest. PV cap.      | GW <sub>p</sub> | 0            | 1024         | 1835         | 2706         |
| Storage capacity      | GWh             | 7131         | 9196         | 10298        | 12185        |
| <b>LEC (530 €/kg)</b> | <b>€/kWh</b>    | <b>0.185</b> | <b>0.139</b> | <b>0.107</b> | <b>0.066</b> |

## 1.4 Conclusions

In this study a comparison has been made on energetic and economical aspects between terrestrial solar power concepts and space power concepts. The results of this study show that space power concepts will not be economically competitive to terrestrial systems for at least the next twenty years. Whether such space concepts may become competitive after this period depends largely on the technological progress made, especially in the area of launching, robotics in space, power to laser/microwave conversion, re-conversion and heat rejection from space elements. From an economic point of view, one of the most critical factors for space systems are the launch costs. Also laser or microwave technology, power transmission and power conversion technology include critical issues to be resolved before space systems can be implemented.

More specifically the conclusions are that terrestrial solar systems in North Africa can cover the load curve of West and Central Europe for levelised electricity generation costs between 0.04 to 0.06 €/kWh at a load higher than 100 GW. Using Solar Power Satellites for electricity supply, a load of more than 1 TW is necessary to reach costs below 0.06 €/kWh. As transportation shows a high contribution to the costs its price is a key parameter and has to be brought down significantly. With the claim of high power levels and its freedom to change the location of a ground receiver with a changing demand distribution on earth, SPS is merely predestined for a global use of this generation system. Looking on a combination of SPS and terrestrial systems no benefits have been detected. Generally, electricity generation from solar energy in North Africa will be competitive in 2020/2030 even compared to conventional power generation. Only a small portion of the desert areas will be necessary

to cover the European demand – even without taking into account generation from other renewables. The energy payback time of all of the investigated systems is low and amounts to several months only. For terrestrial systems the need for seasonal storage can be minimized if oriented optimal. East-West orientation for solar thermal through power systems and two different tilt angles for photovoltaic systems in winter and summer provide nearly a daily constant power production in North Africa. Therefore, expensive hydrogen storage systems are not needed. Pumped hydroelectric storage systems are sufficient to cover the given load curves. Additionally, the corresponding capacities of storage and generation system can be altered within a broad range as the exact dimensioning has nearly no impact on the costs. Transmission losses from North Africa to Europe are between 14 and 18%. Costs for terrestrial power transmission over a distance of 5000 km are in the order of 0.01 €/kWh.

The receiver for solar power from space has very likely also to be placed into desert areas like e.g. the Sahara desert in North Africa. Ground receivers for SPS require large areas of flat and unoccupied land (to avoid possible impact of living species), which will not easy to find in Europe. Also the need for costly storage will go up substantially as Southern Europe faces more days with cloudy skies. The political risks of secure energy supply, dependencies, etc. are mainly comparable for space and terrestrial solutions. The assumptions of the terrestrial systems seem to be rather reasonable as they are based on yet existing technologies with a known history of the technological development in the last years. Nevertheless, the results may deviate by a certain amount as the real future development may differ from the assumptions. The technology for the space system however has to be developed yet, so the taken assumptions are far more insecure. Whereas an installation of the terrestrial systems can take place also in small units, SPS is only worthwhile when installed at high power levels. This requires a high starting investment. A discussion of eventually existing further risks of the energy transmission to earth by laser beam and maybe problems of acceptance by the human population are not subject of this study.

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## 2 Introduction

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Ever since the publication in 1987 of 'Our Common Future' written by the World Commission on Environment and Development (WCED), many authorities and interest groups in policy targets have taken up sustainable development. Sustainable development in energy supply is one of the most important requirements to be met in achieving sustainable development. This is due to the main role played by the supply of energy as a service in realising desired socio-economic developments, and the fact that the way these services are provided confronts society with a series of environmental problems.

One of the main perceived environmental problems related with use of energy is climate change. Continued use of fossil fuel and its related emission of carbon dioxide, the main greenhouse gas in the atmosphere, may lead to dangerous anthropogenic interference with the atmosphere. To avoid such danger, it has been recommended that before the year 2100, the concentration of carbon dioxide should be stabilised at a level below 500 ppm (parts per million), preferably even below 450 ppm. To achieve stabilisation at 450 ppm, the global emission of carbon dioxide should be reduced from the current 6 GtC (gigatonnes of carbon) per year, to a level below 3 GtC per year by the end of next century.

There are a number of options to reduce emissions of carbon dioxide to the atmosphere, i.e. reduction of the energy intensity of the economy, fuel shift to less carbon containing fuels, and enhanced use of nuclear energy. One of the most important options, certainly in the mid-term or the longer term, is the accelerated use of renewable energy sources. The potential of these sources is huge and their future looks promising. Amongst others, studies from the World Bank and the World Energy Council estimated that renewable energy sources could meet more than half of the world's energy needs by the middle of the this century, although it may take twenty years from now before wide-scale application can be realized competitively with fossil fuel technologies. Similar views have more recently been presented by Shell.

A broad range of renewable energy sources is potentially available to contribute to the world's energy need, such as wind, biomass, hydro and solar energy. In this study we make a techno-economic evaluation on the **large-scale implementation of solar energy in Europe**. We make a comparison between large-scale application of terrestrial solar energy and solar power systems in space on technological aspects and costs.

## 2.1 Description of the study

A possible important future renewable energy source is solar energy. Yet, two major concerns slow down its development as an alternative: first, it lacks of technological maturity and secondly it suffers from alternating supply during days and nights, winters and summers.

The idea proposed by Glaser in the 1960s to bypass this inconvenient is to take the energy at the source (or at least, as near as possible): in other words, to put a solar station on orbit that captures the energy without problems of climatic conditions and to redirect it through a beam to earth surface. The principal feasibility was shown in studies in the seventies from the United States Department of Energy and the NASA. There are specific reasons pro, and a similar set of reason contra Solar Power from Space (SPS):

### Advantages of SPS:

- o Much higher quasi-continuous intensity (direct radiation) reduces loss involving storage loops
- o Much lighter less costly construction due to absence of gravity and Earth climatic effects
- o Chance to beam power on the spot on Earth and in Space (Power to where it is needed)

### Disadvantages of SPS:

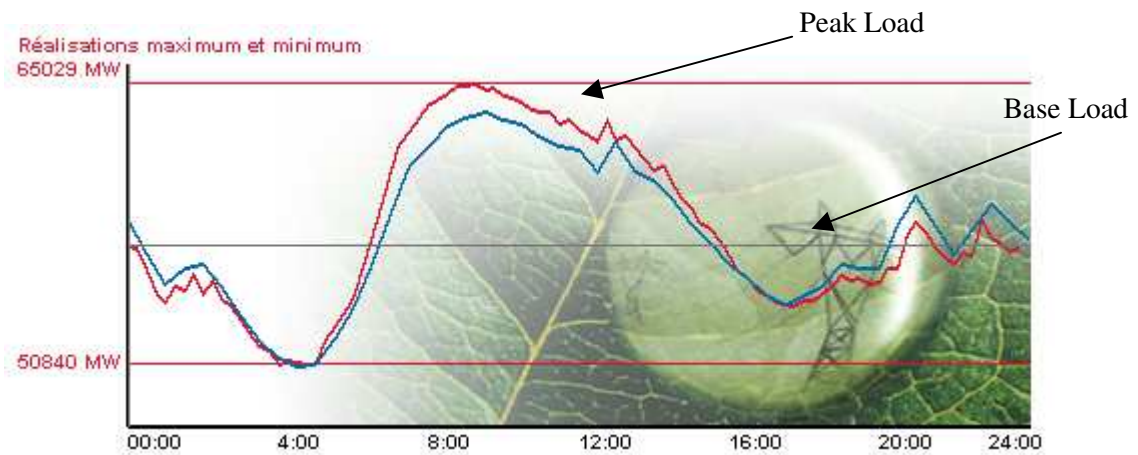
- o Demand for Space Transportation to Space and in Space, (environment, transportation cost)
- o Losses, risks, and safety of wireless power transmission
- o Effort and risk during assembly and operations in hostile environment
- o high initial investment cost

Today, in the course of the study, a severe investigation is needed concerning the question whether solar power systems in space are viable and meaningful in economical, technical and political aspects compared to terrestrial power generation systems.

A point to keep in mind is that the order of magnitude of characteristics involved in SPS concepts (satellites mass, number of launches/year, cost) is far beyond the ones that are considered in current studies. SPS has not to be considered as a pure middle-term space project, like other satellites or probes, but it needs a radical and long-term evolution in energy production. It implies for space industry a change in scale. Instead of ten launches per year, the assembly and maintenance of SPS will require a hundred and more, boosting the production of rockets.

In this study, the European energy market is the starting point of the analysis. It determines both the energy output of the system and the costs limitation. A typical energy consumption profile is shown in the figure below. It highlights three types of targeted market:

- o The base-load market: the purpose is to insure an average but constant load of energy. Endurance of the system is then necessary.
- o The non-base load market: here the system is an assistant to a global energy producer. It does not provide a constant energy output, design margins are greater than in the previous case.
- o The full supply market: here the total demand is covered.



To validate the study performance parameters will be needed. Given the properties of the targeted markets, the performance is determined by:

- Energy efficiency: it is the gain between power brought by sun irradiance and the power available for the customer.
- Costs: it is the cost of assembly, maintenance and energy delivery. This cost is translated into electricity cost for the customer.

Given the size and the complexity of SPS, the purpose of this study is to assess the viability of such concepts, to make compatible the shapes of the system characteristics and to establish a sound trade evaluation between terrestrial and space-based power generation.

In this study we made a comparison between electricity supply from solar power satellites in space and two terrestrial generation systems for several European load curves in several power levels from below 1 GW to full supply. Additionally, combined space-terrestrial scenarios have been investigated, optimized for real load curves.





## 3 Solar Power Satellites from Space

---

### 3.1 Introduction

#### 3.1.1 Solar energy systems in space

Although solar energy is regarded as environmental friendly and virtually available in unlimited amounts, the energy density (energy per volume unity or unit area) is low compared with other energy production systems (nuclear reactor of the type DWR 100 W/m<sup>3</sup>, solar energy approx. 0,001 MW/m<sup>2</sup>). Low energy densities connected with high manufacturing cost mean high investment costs per kW of installed power capacity and high costs per working unity (€/kWh).

With the aim to reduce costs, alternative solar energy systems are examined and investigated. When the main technological problems are solved the orbital solar energy use could become an interesting option on a long-term basis. The investigations executed up to now show clearly that since the seventies new technologies or technological solutions has been developed which make realization of Solar Power Systems closer to realisation.

Some examples of these developments are:

- *Photovoltaic*: efficiency today approximately 12.5 - 15%; in the future efficiencies of more than 20% to maximally 30 to 50% (multi-junction solar cells) can be expected; current specific surface weight amounts to approximately 1.0 kg/m<sup>2</sup>, in the future to approximately 0.2 kg/m<sup>2</sup>
- *Structures*: framework constructions for extreme lightweight construction amounts to approximately 0.1 kg/m<sup>2</sup> specific surface weight for solar generators. With the application of "more intelligently" composite materials, electric viscosity-control of the stiffness and the damping characteristics of the structure at alternate loads (active oscillation damping), specific surface weight of << 0.1 kg/m<sup>2</sup> is conceivable
- *Wireless transfer of energy*: transmission through microwave reach whole efficiency of approximately 46%. Future attainable efficiencies amounts to approximately 68%. Laser reaches currently some per cent of whole efficiency; on the basis of laser diodes approximately 24% of whole efficiency will be attainable. On the basis of solar pumped lasers 50% of whole efficiency is conceivable (whole efficiency is counted by transmitter input to receiver output with laser diodes; with solar pumped laser is counted by mirror input to receiver out)
- *Transportation*: Approximately 5000 \$/kg LEO; 25000 \$/kg GEO (Ariane); 1600 \$/kg LEO; approximately 6000 \$/kg GEO (Energia); Heavy elevator Vehicle in LEO + application of electric engines for LEO/GEO transfer approximately 2000 \$/kg for distance Earth-GEO, future aim: 600 \$/kg Earth-GEO
- *Infrastructure / transport systems*: infrastructure and transport systems for realization of SPS only limited existing; by heavy lift -transporters (Energia, Ariane 5); construction of infrastructure (ISS); transportation of passengers in orbit nearly "Routine" (shuttle, future Launcher)

Recent work concerning the solar energy use has shown that on the one hand substantial development and experimental need exists for technological aspects like accurate pointing, efficiency chain, electric compatibility and on the other hand for research activities to the clarification of the atmospheric load by launchers and energy rays.

The attempt of a "binary" energy supply appears promising. The 'energy radiation' from the orbit by means of laser could supply energy in supplement to the already existing terrestrial photovoltaic systems. In this way an energy supply without day and night cycle around the clock could be guaranteed, without the need for large storage capacity. By the support of a solar energy satellite, the utilization factor of the terrestrial station can so be raised by a factor five to ten, amongst others depending on the geographic location of the photovoltaic receiver station.

Implementation of such concepts could start with the development of terrestrial facilities. Storage can be used to balance the day and night cycles. In a next stage of development, energy "could be fed" additionally by orbital energy stations.

An essential factor by the realization of combined SPS and terrestrial systems is a reliable space infrastructure. The technological development program for this perspective encloses the essential steps:

1. Lab tests on ground for the demonstration of the essential technologies, like the transfer of energy, re- transformation in electric energy, storage, laser pointing, tracking and control, laser systems of high beam quality, efficiency and reliability, thermal control, structure technology, and hydrogen generation and processing
2. Terrestrial experimental arrangements about bigger distances and higher energy levels
3. Space-experimental arrangements, e.g. using the international space station ISS as a technology carrier; transfer of energy from the ISS to ground and demonstration of enabling technologies
4. Space-demonstration arrangement as independent, free-flying satellite that supplies energy to a "consumer" or customer, e.g. a research station
5. Industrial pilot's arrangement, modular extendable space concept to feed into terrestrial energy systems; worldwide flexible energy availability at the "customer's location"

A safe and economically justifiable access to space is an essential presupposition. Development investments in non-core business-type technologies, like laser as a system design driver are necessary.

### **3.1.2 Solar power activities recall**

Dr. Peter Glaser developed the SPS concept in the sixties. At that time it was concluded that the technology was not yet available. The feasibility of the technology was shown by DOE / NASA in the frame of 1970s Studies (5 GW SPS in GEO).

In general, the conceptual approach was as follows:

|                     | <b>Baseline Solution</b> | <b>Back-up Solution</b> |
|---------------------|--------------------------|-------------------------|
| Power Generation:   | Photovoltaic             | Solar-dynamic           |
| Power Transmission: | $\mu$ -wave @ 2.35 GHz   | Laser                   |
| Re-conversion:      | Rectenna                 | Thermodynamic           |

The use of microwave power transmission involved the following concerns:

- o Large transmission antenna (1.3 km radius), large ground rectenna (15 km radius)
- o Diffraction limited long distance  $\mu$ -wave WPT; intensity limits (23 mW/cm<sup>2</sup>)
- o Long time exposure limits of biological material to  $\mu$ -wave (side lobes and spikes)
- o Safe, clean, affordable access to space

The main conclusions from a number of investigations were:

- o DOE/NASA 1970s studies showed the feasibility, but first step was found too expensive. This conclusion was confirmed by follow-up studies (ESA and Germany)
- o The NASA Fresh Look Study (1995 /-1997) stated that the access to space is still too expensive
- o The NASA SERT Programme (1998 - ) was to conduct preliminary strategic research investigation and to re-evaluate the SPS concepts

## **3.2 Overview for solar power concepts**

In close iteration with the terrestrial systems approach of DLR, the following general proceeding has been carried out:

- o Screening and outline of SPS concepts
- o Key technology assessment
- o Power transmission technology assessment
- o Proceeding with deeper performance investigation of a reference SPS which covers varies profiles, and provides a combined solar power solution, using natural sunlight and power from space simultaneously.

### **3.2.1 Concept listing**

A broad variety of SPS concepts has been created and evaluated in the past; this was performed by European, American, Japanese, e.al.sites, done by industry and organizations, like NASA, ESA or DLR.

Hereunder a selection of SPS systems is given. The most important systems will be treated as candidates in this study, as the so called 'state-of the-art' SPS concepts.

#### **1. Concepts 1968 - 1985**

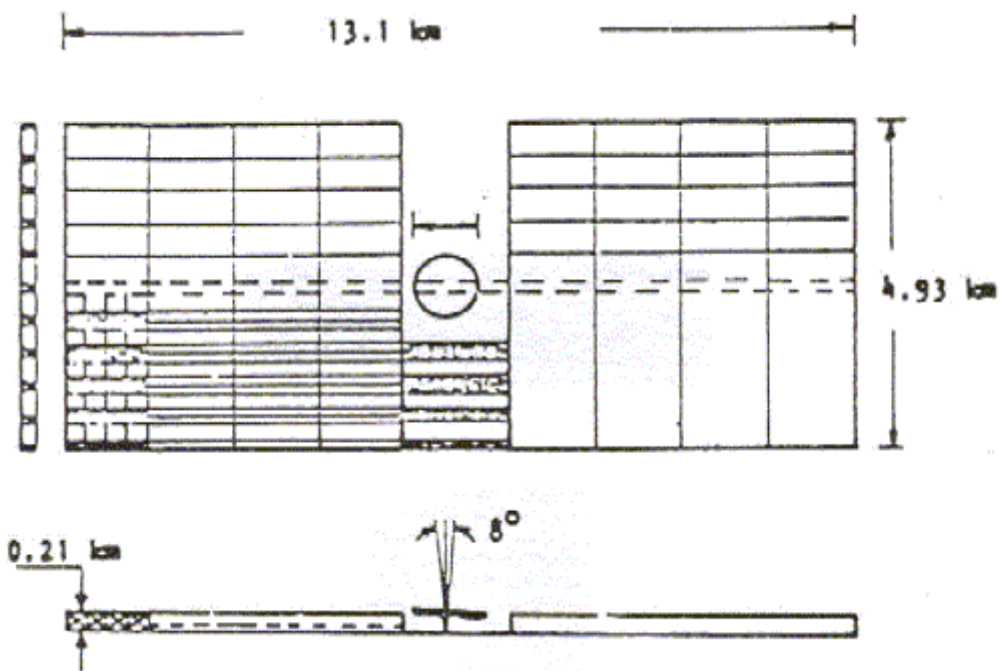
- o SPS Concept of A.D. Little 1968
- o Solar Thermal SPS Boeing 1974
- o DOE/NASA Reference Concept 1978 Si Option
- o DOE/NASA Reference Concept 1978 GaAs Option
- o Boeing SPS Concept 1978
- o Rockwell SPS Concept 1978
- o GSSPS Concept by Aerospace Corporation

- o MOSES Concept 1979
  - o Japan's Space Energy Program Hitachi Version
  - o NASA Lunar Base SPS 1985
- 2. European Concepts 1968 - 1990**
- o 10 GW Orbital Solar Energy-Station by DASA/MBB
  - o GSEK 1 MW Demonstration Station
  - o SPS Experimental Proposal GSEK 1 KW DASA/MBB
  - o SPS Experimental Proposal EUROSPACE
- 3. Recent Concepts**
- o Basic Sun Tower (Sun-Tracking)
  - o Basic Sun Tower (Two-Sided)
  - o Abacus Sun Tower (Sun-Tracking)
  - o Abacus Sun Tower (Two-Shielded)
  - o Abacus Reflector
  - o Integrated Symmetrical Concentrator (ISC) High Concentration Ratio
  - o Integrated Symmetrical Concentrator (ISC) Low Concentration Ratio
- 4. NASA Fresh Look Study Concepts**
- o Solar Disc (Fresh Look Study)
  - o Sun Tower (Fresh Look Study)
  - o Solar Power Tower (SE&U Study)
- 5. NASDA Concepts**
- o SPS 2000 (Nasda)
  - o Reference System

### **3.2.2 SPS concepts outline**

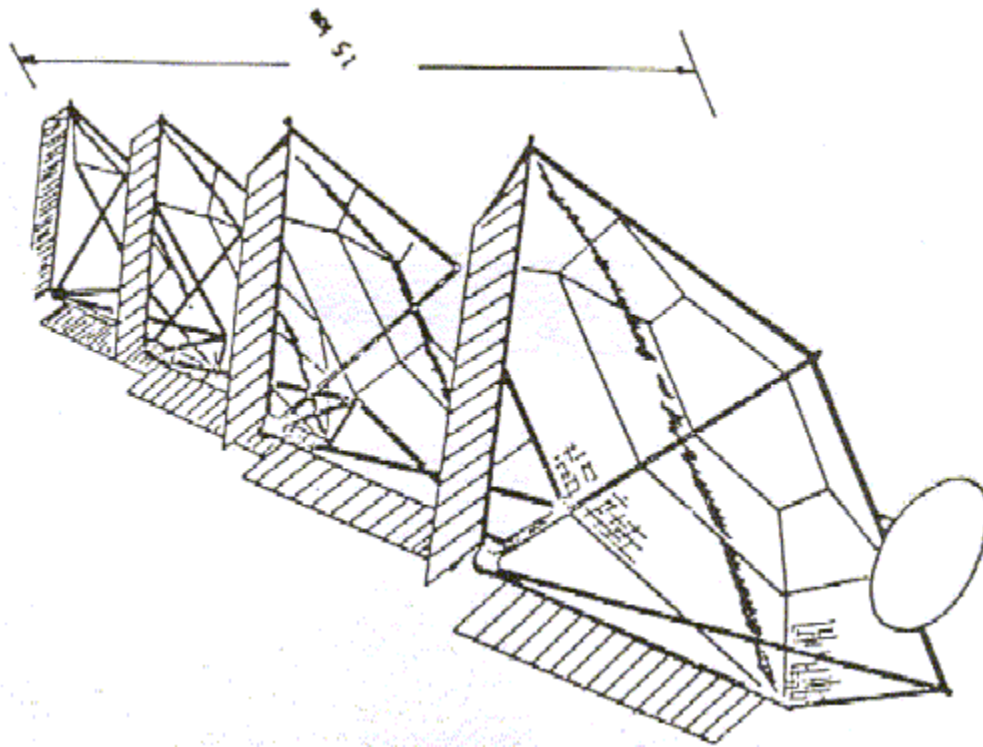
The SPS concepts what has been taken into a closer consideration within the study work are outlined by their main system and performance characteristics.

#### **1. SPS Concept of A.D. Little 1968**



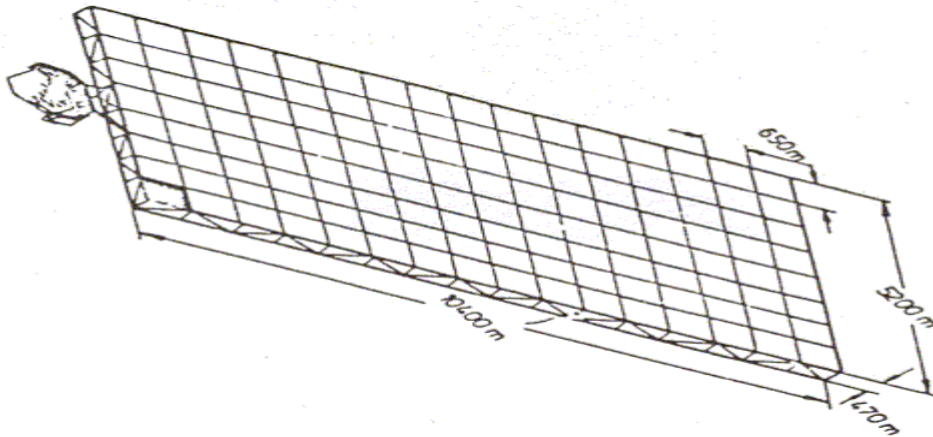
|                          |                                |
|--------------------------|--------------------------------|
| Ground Power Output      | 5 GW                           |
| Total Mass               | 18 x 10 E06 kg                 |
| Solar Cell Type          | 50 $\mu$ m SI Cells            |
| Efficiency               | 14 % BOL                       |
| Microwave Generator Type | Amplitron                      |
| Generator Efficiency     | 87 %                           |
| System Efficiency        | 6.74 BOL                       |
| Total Cost (w/o DDT&E)   | USD 1500/kW or USD 7.6 billion |
| Electricity Cost         | 27 Mills/kWh                   |
| DDT&E Cost               | USD 44 billion                 |

## 2. Solar Thermal SPS Boeing 1974



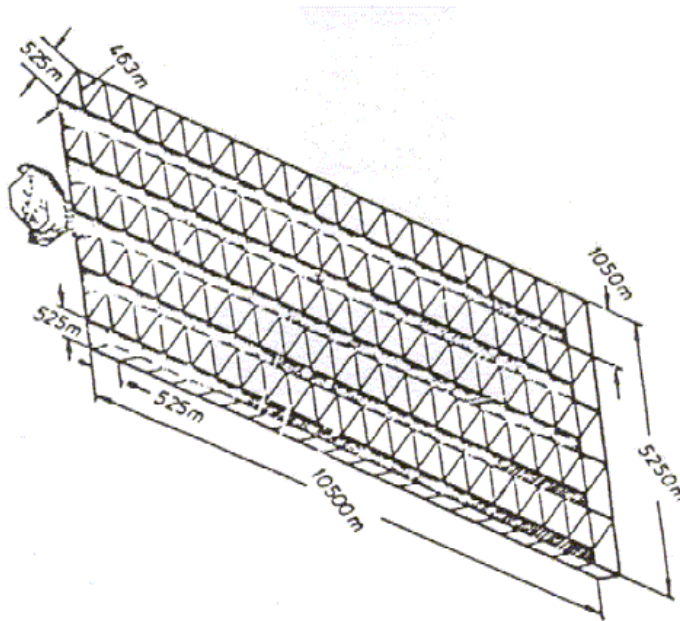
|                                                    |                              |
|----------------------------------------------------|------------------------------|
| Ground Power Output                                | 10 GW                        |
| Total Mass                                         | 80 x 10 E06 kg               |
| Conversion                                         | Brayton Cycle / Turbomachine |
| Concentration Ratio                                | 1500                         |
| Cycle Thermal Efficiency                           | 40 %                         |
| SPS System Cost                                    | USD 700/kW                   |
| (w/o transport, construction,<br>rectenna & DDT&E) |                              |
| Transportation Cost                                | USD 400 - 770/kg             |

### 3. DOE/NASA Reference Concept 1978 Si Option



|                          |                       |
|--------------------------|-----------------------|
| Ground Power Output      | 5 GW                  |
| Total Mass               | 51 x 10 E06 kg        |
| Blanket Area             | 52.34 km <sup>2</sup> |
| Conversion               | Si Solar Cells        |
| Efficiency               | 16.5 %                |
| Microwave Generator Type | Klystron              |
| Generator Efficiency     | 85 %                  |
| Total Cost Estimate      | USD 2000/kW           |

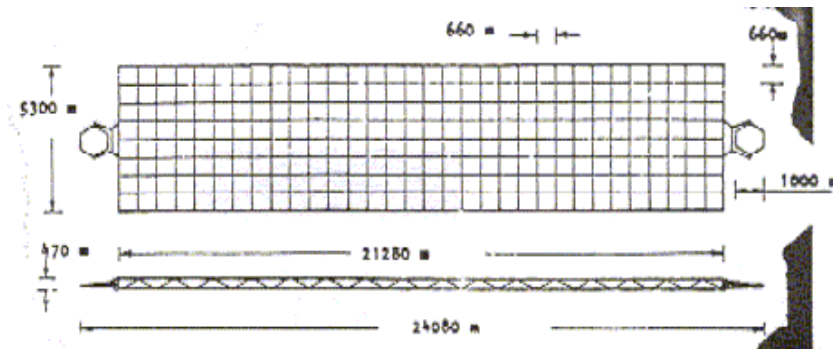
#### 4. DOE/NASA Reference Concept 1978 GaAs Option



|                          |                       |
|--------------------------|-----------------------|
| Ground Power Output      | 5 GW                  |
| Total Mass               | 34 x 10 E06 kg        |
| Blanket Area             | 26.52 km <sup>2</sup> |
| Reflector Area           | 53.04 km <sup>2</sup> |
| Conversion               | GaAs Solar Cells      |
| Efficiency               | 18.2 % at 125 degC    |
| Microwave Generator Type | Klystron              |
| Generator Efficiency     | 85 %                  |
| Total Cost Estimate      | USD 2700/kW           |

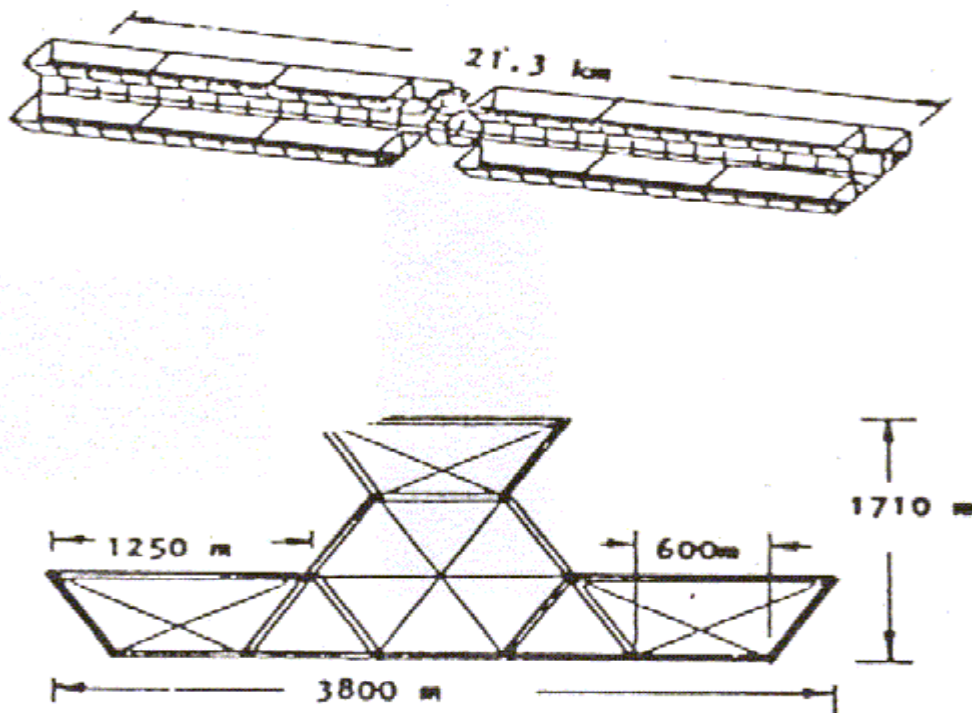


## 5. Boeing SPS Concept 1978



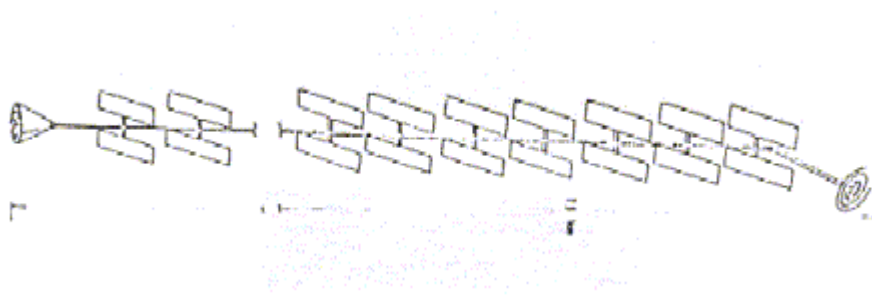
|                          |                   |
|--------------------------|-------------------|
| Ground Power Output      | 10 GW             |
| Total Mass               | 90 x 10 E06 kg    |
| Conversion               | 50 microm Silicon |
| Efficiency               | 17.3 %            |
| Microwave Generator Type | Klystron          |
| Generator Efficiency     | 85 %              |
| System Efficiency        | 7,12 %            |
| Total Cost Estimate      | USD 2000/kW       |
| Electricity Cost         | 35 Mills/kWh      |

6. Rockwell SPS Concept 1978



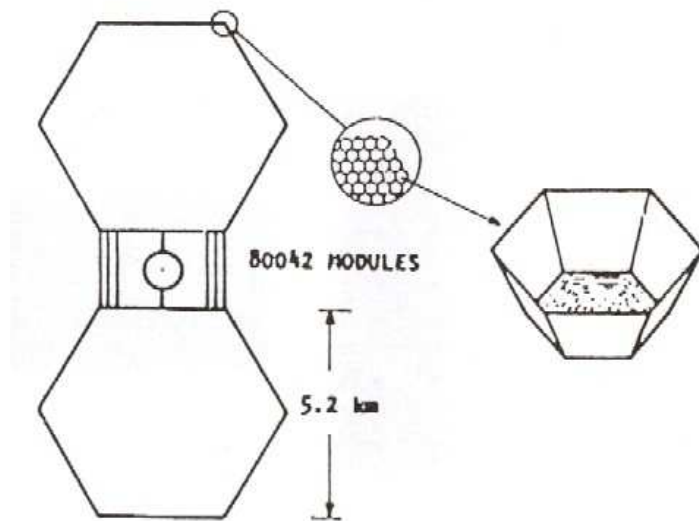
|                          |                   |
|--------------------------|-------------------|
| Ground Power Output      | 5 GW              |
| Total Mass               | 36 x 10 E06 kg    |
| Conversion               | GaAs Solar Cells  |
| Efficiency with CR=2     | 17.6 %            |
| Microwave Generator Type | Klystron          |
| Generator Efficiency     | 85 %              |
| Total Cost Estimate      | USD 2700/kW       |
| Electricity Cost         | 40 - 80 Mills/kWh |

## 7. GSSPS Concept by Aerospace Corporation



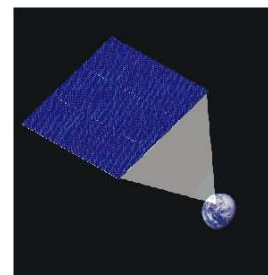
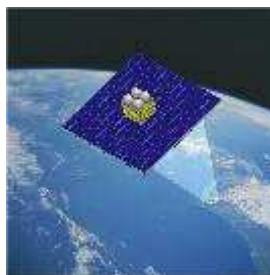
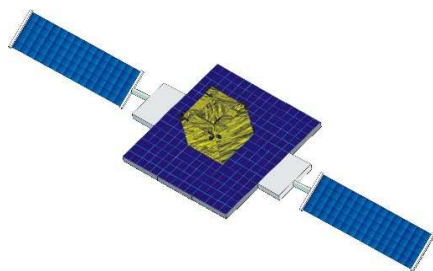
|                          |                  |
|--------------------------|------------------|
| Ground Power Output      | 5 GW             |
| Total Mass               | 20 x 10 E06 kg   |
| Conversion               | GaAs Solar Cells |
| Efficiency               | 22 %             |
| Microwave Generator Type | Solid State      |
| Generator Efficiency     | 80 %             |
| System Efficiency        | 9.1 %            |

## 8. MOSES (Modular Energy Satellite) Concept 1979



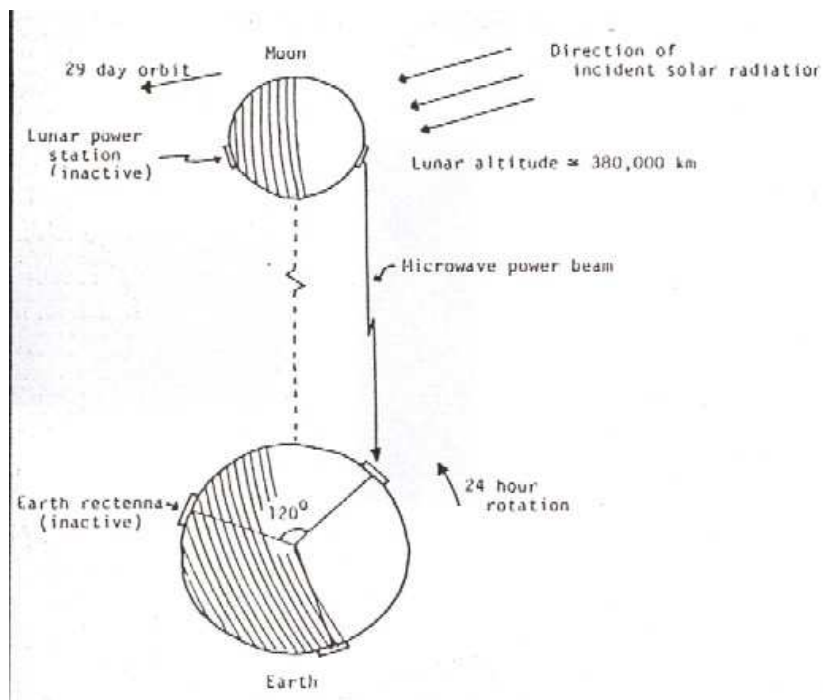
|                                     |                  |
|-------------------------------------|------------------|
| Ground Power Output                 | 5 GW             |
| Total Mass                          | 30 x 10 E06 kg   |
| Conversion                          | GaAs Solar Cells |
| Efficiency with CR=2                | 18 %             |
| Total Cost Estimate<br>(w/o DDT&E)  | USD 1400/kW      |
| Electricity Cost<br>(1973 estimate) | 7 - 13 Mills/kWh |
| Module Size                         | 30 m Diameter    |
| Module Power                        | 100 kW each      |

## 9. Japan's Space Energy Program Hitachi Version



|                  |            |             |          |
|------------------|------------|-------------|----------|
| Configuration    | Experiment | Pilot Plant | SPS      |
| Size             | 20mx50m    | 400mx800m   | 4kmx18km |
| Generation Power | 50kW       | 10 MW       | 10 GW    |

# 10. NASA Lunar Base SPS 1985



Ground Power Output 5 GW

3 Earth Stations

2 Lunar Power Stations

5% Efficient Solar Cells made from Lunar Materials

80 km<sup>2</sup> Power Transmission (100xSPS-GEO)

3x300 km<sup>2</sup> Earth Rectenna

Cost Factor 8 in comparison to SPS-GEO



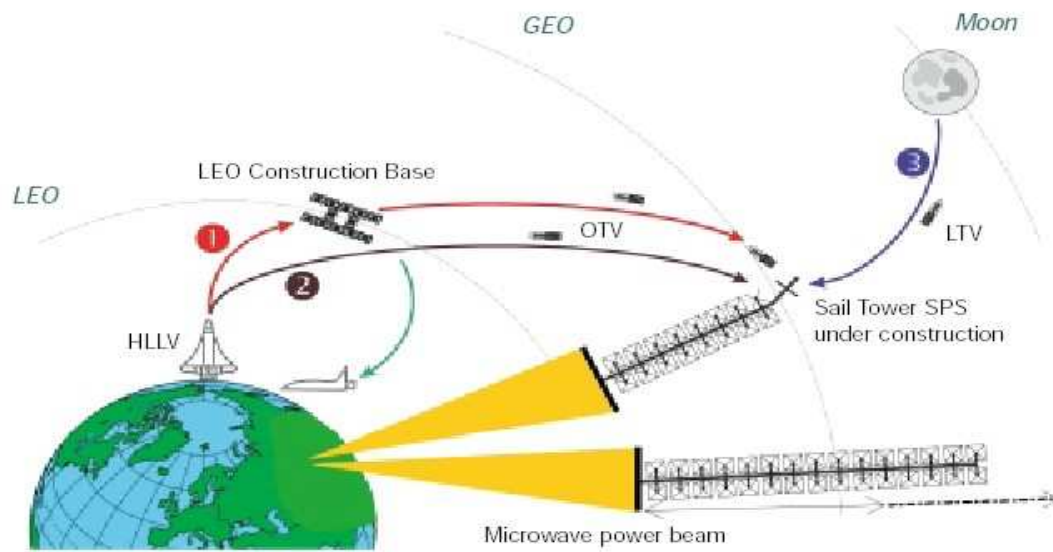
### 13. SPS Experimental Proposal EADS-GSEK 1 KW

|                               |                                       |
|-------------------------------|---------------------------------------|
| Total Mass                    | 4200 kg                               |
| Power Transmission            | GEO/Earth                             |
| Laser                         | Monolithic, Halogen-Pumped Slab Laser |
| Fine Pointing Accuracy        | 0.05 arc sec                          |
| Laser Power Output            | 1 kW                                  |
| Power Consumption             | 11 kW                                 |
| Launch System                 | Ariane 4                              |
| Total Program Cost Estimation | 400 MioDM                             |
| Experiment Preparation        | 5 -8 a                                |
| Mission Duration              | 12 Months                             |

### 14. SPS Experimental Proposal EUROSPACE

|                                           |                                |
|-------------------------------------------|--------------------------------|
| Power Level                               | 1 kW Laser                     |
| High Accuracy Pointing at 10 km distance  |                                |
| Fine Pointing Accuracy better             | 0.1 arc sec                    |
| Reflector on Target Spacecraft Astro-Spas |                                |
| Power Density                             | 10 kW/m <sup>2</sup>           |
| Laser Type                                | Diode Pumped Solid State Laser |
| Laser Transmission                        | 0.5 km                         |
| Total Program Cost Estimation             | 400 MioDM                      |
| Experiment Preparation                    | 4 a                            |

## 15. European Sail Tower Concept

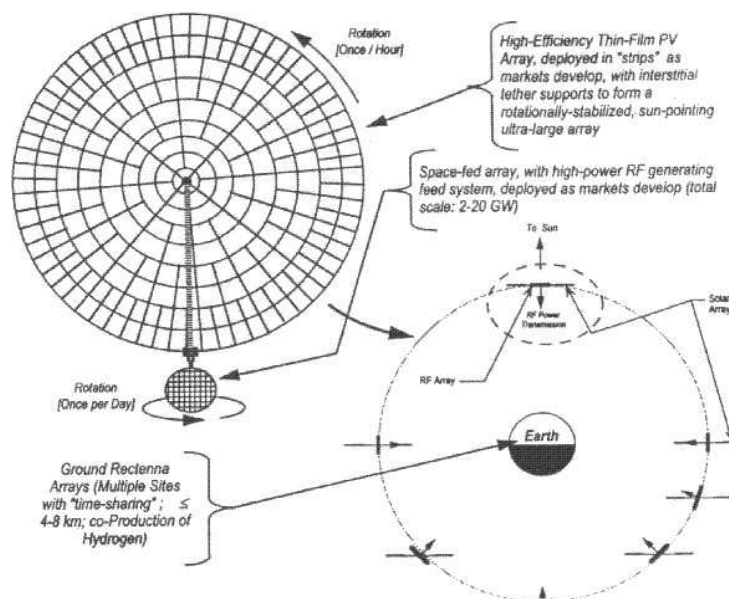


|               |                    |      |                     |
|---------------|--------------------|------|---------------------|
| Orbit         | GEO                | Cost | 124 B€ production   |
| No of Systems | 1870               |      | 0.92 B€ transport   |
| Lifetime      | 60 yrs             |      | 18 B€ rectenna/5 GW |
| SPS Tower     | 2140 mt mass       |      | 265 be development/ |
|               | 15 km length       |      | 0.075 €/kWh         |
|               | 450 Mwe1           |      |                     |
| MW Antenna    | 400.000 magnetrons |      |                     |
|               | 510 m radius       |      |                     |
|               | 1600 mt mass       |      |                     |
|               | 400 MW             |      |                     |
| Rectenna      | 103 final No       |      |                     |
|               | 11x14 km (27x30)   |      |                     |



## 16. Solar Disc (NASA Fresh Look Study)

### NASA Solar Disc Configuration and orbital performance



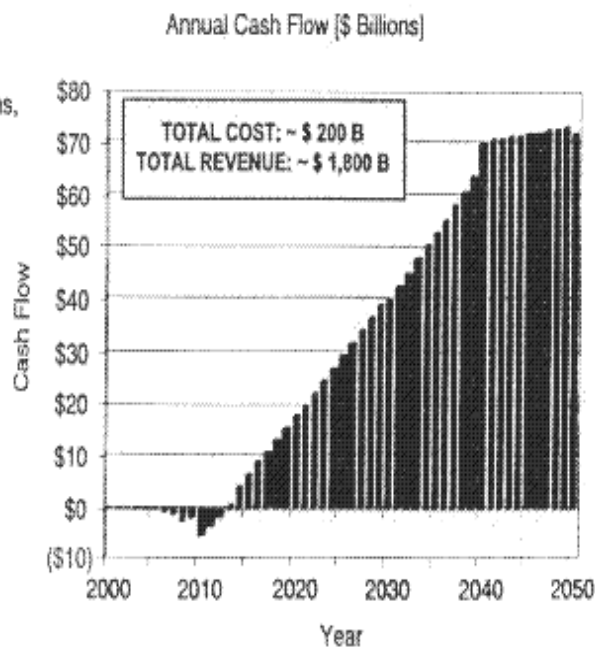
### Solar Disc Basic Economical Data

#### A Possible Scenario

- Government-Industry partnership develops and demonstrates SPS technology
- Initial commercial MEO constellation matures systems, establishes basis for larger investment
- Commercial GEO SPS system development, deployment & operation "privately"-financed
  - 6 satellites launched over 30 yrs
  - 1 Ground Receiver per SPS
  - Total SSP Power =  $6 \times 5 \text{ GW} = 30 \text{ GW}$
  - SPS Lifetime = 40 years
  - 25% SPS Mass Refurbished every 20 years
  - Launch Services @ \$400/kg
- Government(s) legislation enables "externalities" surcharge (renewable energy)

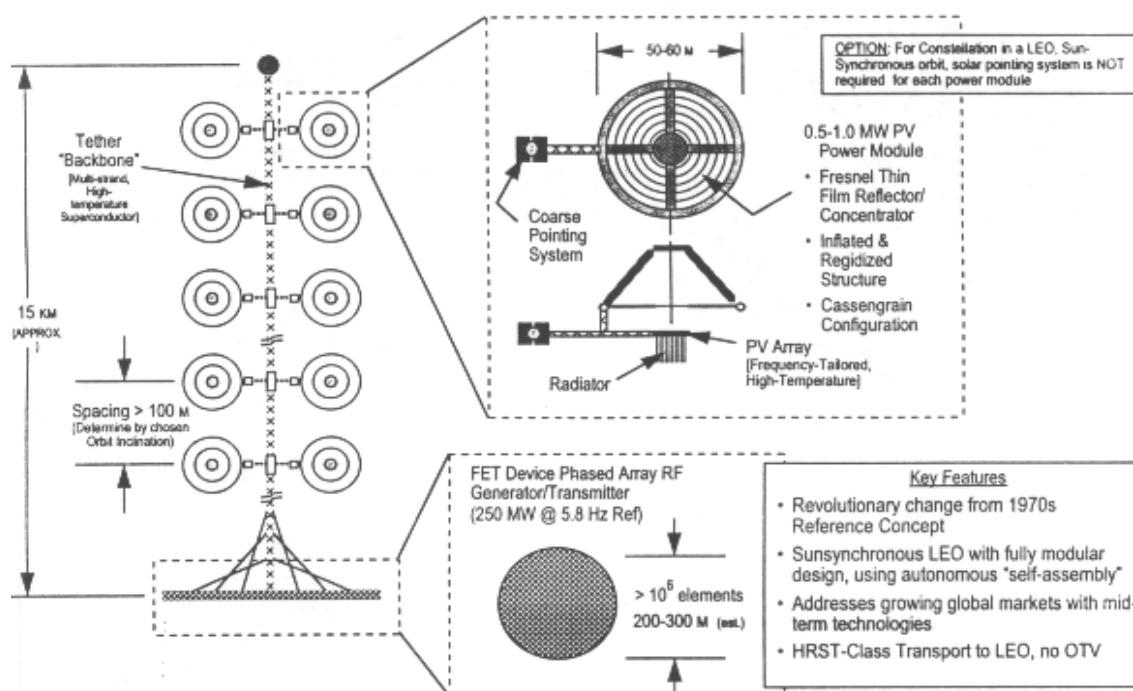
#### The Result

- Commercial cost-to-first-power ~ \$30-40B
- Constellation Installation Cost ~ \$150B (~\$5/W)
- IRR ~ 27.6 %
  - Average Power Cost ~ 2 ¢/kW-hr
  - Average Power Price ~ 28 ¢/kW-hr



## 17. Sun Tower (NASA Fresh Look Study)

NASA Sun Tower Configuration and orbital performance:



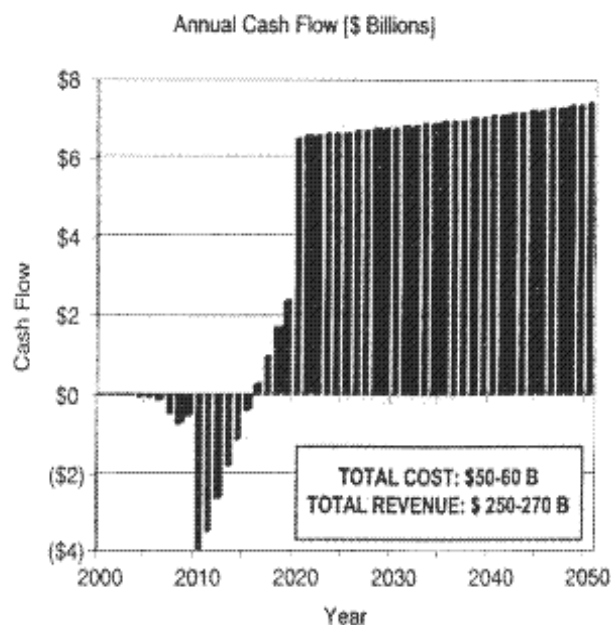
NASA Sun Tower Basic Economical Data:

### A Possible Scenario

- Government-Industry partnership develops and demonstrates SPS technology
- Commercial SPS system development, deployment & operation "privately"-financed
  - 18-24 satellites launched over 10 yrs
  - 1 Ground Receiver per SPS
  - Total Constellation Power = 3.5-4.0 GW
  - SPS Lifetime = 40 years
  - 10% SPS Mass Refurbished every 10 years
  - Launch Services @ \$400 / kg
- Government(s) legislation enables "externalities" surcharge (renewable energy)

### The Result

- Commercial cost-to-first-power ~ \$6-8 B
- Constellation Installation Cost ~ \$35-40B (~\$10/W)
- IRR ~ 15 %
  - Average Power Cost ~ 4 ¢/kW-hr
  - Average Power Price ~ 21 ¢/kW-hr



### 3.2.3 Solar power concepts comparison

A comparison and overview of the mentioned SPS concepts is done within the Table 1, also the most essential system parameters are given, as output power, system mass, size, conversion and

Table 21: Comparison of Selected Solar Power Concepts

| Major SPS Concepts - Data                    | Power Output |             | Mass   | Size                  |                  | Conversion Transmission |                          | Efficiency |     |                    | Cost B USD/€            |            |               |                    | Cent/ kWh Cost/ Price |
|----------------------------------------------|--------------|-------------|--------|-----------------------|------------------|-------------------------|--------------------------|------------|-----|--------------------|-------------------------|------------|---------------|--------------------|-----------------------|
|                                              | Space        | GND         | Space  | Space                 | GND              | Space                   | GND                      | Space      | GND | Total              | Space                   | GND        | TRP           | Total              |                       |
| European Sail Tower™ (18 Sail Tower p. Rect) | 400(450) MW  | 275 MW      | 2126 t | 15 km (150x300x50 m3) | 11x14 km (x 103) | PV & Magnetron 2,45 GHz | Diodes/ Schottky B.Diode |            |     | 12 % %             | 266 (tot incl LV)       | 18 p. 5 GW | 0,92          | 285                | 7,5                   |
| NASA Reference Concept I                     |              | 5 GW each   | 51 kt  | 52,34 km2             |                  | SI PV Cell Klystron     |                          |            |     | 16,5 % (36,5 degC) |                         |            |               |                    | 2000 \$/kW            |
| NASA Reference Concept II                    |              | 5 GW each   | 34 kt  | 26,52km2              |                  | GaAlAs PV Cell Klystron |                          |            |     | 18,2 % (125 degC)  |                         |            |               |                    | 2700\$/kW             |
| NASA Solar Disc                              | < 8 GW       | 5 GW single |        | < 6 KM                | 5-6 km           | PV & 5.8 GHz            | Rectenna                 |            |     |                    | 150 6 Sats 30-50 (5 GW) |            | 200-400 \$/kg | 200 6 Sats (30 GW) | 2 / 26                |
| NASA Sun Tower                               | 100-400      |             |        | 15 km                 |                  |                         |                          |            |     |                    | 35-40 18-24 Sats        |            |               |                    |                       |

|                                                                          |                  |                       |             |                                                |                 |                                      |                |                                     |               |     |                |  |              |       |                 |
|--------------------------------------------------------------------------|------------------|-----------------------|-------------|------------------------------------------------|-----------------|--------------------------------------|----------------|-------------------------------------|---------------|-----|----------------|--|--------------|-------|-----------------|
| MEOSunSynch,<br>1000km                                                   | MW<br>single     | 3,5-4 GW<br>total     |             | length<br>dual 50-100 m                        | 4 km            | PV & 5.8<br>GHz                      |                |                                     |               | 6 % | 8-15<br>250 MW |  | 400<br>\$/kg | 50-60 | 4/21            |
| NASDA<br>SPS 2000<br>(Equatorial<br>1100 km)                             | 10 MW            | 4-4,5 MWh<br>per site |             | 303x336m<br>triangular                         |                 | PV &MW<br>Phased<br>Array            | MW<br>Rectenna |                                     |               | 6 % |                |  |              | 0,09  | 9               |
| Abacus<br>Concepts                                                       |                  | 1-2GW                 | 24-33<br>kt |                                                |                 |                                      |                |                                     |               | 8 % |                |  | 400\$/kg     | 11-19 | 20-30<br>43 MTA |
| Integrated<br>Symmetrical<br>Concentrator<br>High & Low<br>Concentration | 1,3 GW<br>single | 30 GW<br>total        | 18 - 32 kt  | 5 x 15 km<br>(2 units &<br>centr.<br>Transmit. | 6,5 x 8,5<br>km | PV &<br>2.45/5.8<br>GHz              | Rectenna       | PV 35-<br>50%<br>RF > 80%<br>MW 90% | Rect ><br>85% | 30% |                |  |              | 12    | 20              |
| EADS-GSEK                                                                |                  | 10 GW                 | 62<br>kt    | 110 km2                                        |                 | Thin F. SI<br>PV<br>Laser 1,064<br>m |                |                                     |               | 5 % |                |  |              |       | 7               |
| Sandwich<br>Kobe Univ                                                    |                  | -                     | 10 kt       |                                                |                 | 5,8 GHz                              |                |                                     | 10-15%        |     |                |  | 4            | 10    | 8               |

### 3.3 Technology evaluation

#### 3.3.1 Key technologies

The major technology items for Solar Power Systems, which has been assessed in this study, are separately listed below. In the attachment of this report a more detailed technology evaluation is given out of the literature.

- **Space Segment**

Power Infrastructure as core of the SPS:

- o Robust low mass efficient long-life (power generation, wireless power transmission)
- o Fail safe tracking & pointing
- o Beam shaping & control
- o Electric station/attitude control
- o Very large weak structures (construction & control In-situ maintenance)

Support Segment elements for servicing, maintenance, repair and re-supply:

- o Robotic and manned ops
- o Space port with habitation
- o Robotic construction yard
- o Harbours for Tug and Ferry fleet
- o Propellant storage & refuelling
- o IO spare parts inventory
- o Navigation and traffic control
- o Communication network
- o Remote robotic assembly
- o Remote robotic maintenance
- o Automated RVD

Earth To Orbit Transportation:

- o Hopper evolved RLVs (Hooper as semi-reusable launcher system)
- o Adler type semi-reusable HLLVs, with the characteristics,
  - high reliability
  - high performance
  - ultra-low specific cost
  - automated rapid ground operations
  - autonomous flight operations In orbit reutilisation (Adler)

- **Ground Segment**

Power Infrastructure elements for reception, conversion and distribution:

- o Efficient low scatter reception
- o Efficient re-conversion to DC

- o High efficiency energy storage
- o Long range transmission (high voltage DC, hydrogen pipelines)
- o Interconnection to user grids
- o Management of distribution
- o Remote *SPI* control stations

Support Segment for manufacturing, launch and operations:

- o Large scale industrial production of RLVs, HLLVs, Tugs, Ferries
- o Logistics and ground transportation
- o Space ports for high frequent launch
- o High frequent launch operations

### **3.3.2 Power transmission technology**

- **Power Beaming Basic Technologies Characteristics**

The beaming or wireless transmission of power relies either on microwave or laser technology. In this study both ways has been treated, but major emphasis is lain on laser systems. A rough comparison of laser and microwave transmission is briefly discussed hereafter. A diffraction limited focus and propagation principle is applied.

Thereby, two basic concepts exist:

a.) Micro-Wave (*Wavelength ca. 1 cm*)

The issues are here:

- o Short transmission distance or large apertures or higher frequency
- o 2.35 GHz with excellent efficiency state of the art
- o Higher frequencies (35 GHz to 60 GHz) at a reduced efficiency

b.) Laser (*Wavelength ca. 1  $\mu$ m*)

The issues are here:

- o Good beam focussing over very long distance, but low efficiency
- o Thermal stability of receptor limits core intensity (waste heat)
- o Beam jitter and potential damage at high concentration

It has to be noted that a Gaussian intensity distribution needs attention (exponential intensity decay in radial direction). The receptor aperture close to first dark ring is good for a reasonable collection efficiency (ca. 83 to 89%). The intensity in first fringe (side lobes) has to be kept below prescribed limits.

Looking to laser power transmission, the main requirements on Lasers for Power Beaming from space are:

- Efficiency is important especially for space borne systems in view of heat rejection, but is also a major criteria with respect to economics of the system
- The source (beam generator) properties must match with the receiver system. For instance the pulsed lasers are incompatible with photovoltaic retransformation, because the receiver for the peak pulse power is orders of magnitude above average pulse power
- Incompatibility must also be assumed for thermal infrared sources like CO<sub>2</sub> laser because of the lack of photovoltaic converters.

The reasoning for giving the preference on laser power transmission technology in this study is mainly to avoid the drawbacks of microwave transmission. In microwave transmission systems side lobes/spikes occur and they are difficult to control in failure cases and they have much higher mass and sizing requirements of the transmitting elements compared to the laser system (up to factor of 50), despite the relatively high microwave efficiency and the technology development status, achieved up today.

The laser technology is preferred versus microwave concerning distinct criteria, but both microwave and laser technology have been assed:

- transmission elements size
- side-lobes/spikes issue
- negative impacts of MW (navigation, communication, human / environment)
- laser modular implantation

Summarizing these actual arguments of laser versus microwaves the following could be stated:

- Microwave systems are relatively efficient and provide less attenuation by atmospheric effect
- R/F spectral constraints on MW side-lobes and grating-lobes imposed by the ITU result in design and filtering requirements; this leads to reduced efficiency and larger, more costly systems
- Laser systems allow a smooth transition from conventional power to SPS and offer more useful space applications and open up new architecture solutions
- Electronic laser beam steering probably required to keep mechanical complexity and mass within acceptable limits
- Laser and microwave systems have different design drivers, and due to their potential, laser based systems deserve a comparable consideration
- In terms of launch, transportation and assembly efforts, microwave systems are more complex and costly compared to laser systems (big transmitter antenna)

In the process of power transmission technology evaluation, the identification of a most suitable laser system (or microwave system) relies on certain criteria. These criteria need to be judged in context of the actual SPS application.

In short the selection criteria of lasers for power beaming applications are:

- Maximum average power per unit
- Efficiency of laser head, power supplies and auxiliary equipment
- Beam parameters (in context with beam shaping optics)
- Wavelength
- Back-conversion
- Reliability and lifetime

- o Heat rejection
- o Mass and volume
- o Modularity and coupling of units

In Table 22 and Table 23 a comparison from a laser manufacturer to efficiencies and system properties for candidate laser systems is presented.

Table 22. Comparison of Industrial Laser Types Efficiencies

| Type                         | Wavelength         | Wall Plug Efficiency [%], laser head only | System Efficiency [%], Chiller and power supplies included |
|------------------------------|--------------------|-------------------------------------------|------------------------------------------------------------|
| CO <sub>2</sub> -Flowing Gas | 10.6 $\mu\text{m}$ | 12                                        | 6                                                          |
| Nd:YAG (lamp pumped)         | 1.06 $\mu\text{m}$ | 1-2                                       | 0.5                                                        |
| Diode Pumped Nd:YAG          | 1.06 $\mu\text{m}$ | 8-12                                      | 4-6                                                        |
| Direct Diode                 | 0.8 $\mu\text{m}$  | 50-60                                     | 25-30                                                      |

Table 23. Laser Types Characteristics

| Laser Types and Characteristics | CO <sub>2</sub>      | Nd:YAG (Diode pumped) | Single Diode         | Diode Bar            | Diode Stack          |
|---------------------------------|----------------------|-----------------------|----------------------|----------------------|----------------------|
| Maximum Average Power per Unit  | 20kW                 | 5kW                   | 1W                   | 100W                 | 3kW                  |
| Efficiency                      | 25%                  | 15%                   | 40%                  | 30%                  | 30%                  |
| Beam Parameter Product [m rad]  | 1 x 10 <sup>-5</sup> | 3 x 10 <sup>-5</sup>  | 2 x 10 <sup>-6</sup> | 2 x 10 <sup>-5</sup> | 3 x 10 <sup>-4</sup> |
| Wavelength                      | 10 $\mu$             | 1 $\mu$               | 0.7-0.9 $\mu$        | 0.7-0.9 $\mu$        | 0.7-0.9 $\mu$        |
| Back-conversion                 | thermal              | Silicon cells         | GaAs cells           | GaAs cells           | GaAs cells           |
| Reliability and Lifetime        | 10000h               | 25000h                | 25000h               | 25000h               | 25000h               |
| Heat Rejection                  | +                    | 0                     | ++                   | ++                   | +                    |
| Mass and Volume/power           |                      |                       |                      |                      |                      |
| Coupling                        | 0                    | 0                     | +                    | -                    | --                   |
| Supplies                        | 1l/h/kW Gas          | -                     | -                    | -                    | -                    |

For power beaming from GEO to Earth there are 3 alternatives for further laser systems development:

1. Diffusion cooled sealed-off CO<sub>2</sub> slab lasers (in combination with thermo-dynamic re-conversion) provide a just acceptable efficiency, which however has little potential to be improved any further. These lasers feature the highest power per unit with still more than sufficient beam quality. Some deficiencies in lifetime need improvement
2. Nd:YAG lasers combined with photovoltaic re-conversion at reasonable efficiency (silicon cells), however the efficiency of the lasers as of today is not sufficient. Heat rejection is a



major problem, slab lasers may be a way out in future development. High power per unit results in more difficult to handle beam quality

3. High power diode lasers provide an NOT acceptable beam quality for this application, because they are, due to the very low power per unit, based on single diodes which are optimised for output power and not for beam quality. Stacking of these devices results in further deterioration of beam parameters, which is not disturbing in near distance focussing, however destroys the beam with respect to long range collimation from GEO

Since beam quality of the single diode has already been improved up to the diffraction limit, there are essentially three potential ways for future development:

- o *Individual collimation optics per diode*  
This means that each diode has to have a diffraction limited beam quality ( $M^2=1$ ) with a reasonable power ( $> 1W$ ) and each will be equipped with its dedicated collimation optics. The problem may arise in the alignment and stability of the alignment of the extreme number of tiny emitters needed for power transmission to a defined spot
- o *Combining the beams of many laser diodes into a single collimation optic*  
It is assumed that this is only possible by stacking (combined with polarization and wavelength decoupling methods as described above) as used in today power diode lasers and thus will improve (with respect to 3a) the cumulated aperture needed, if the beam quality of the single diode can be kept at high level
- o *Coherent coupling of diode lasers to form a common wave front*  
This implies employing the MOPA concept to multiple amplifiers in parallel. All coupled diodes share the same collimating optics or may even form a synthetic aperture

A more conceive comparison of a set of the most like laser systems, which are in closer look for future solar power transmission applications is given in the next Table 24. The cases of a solid-state laser, chemical laser and direct solar pumped laser are compared. The chemical laser provides especially due to its logistic material re-supply requirement for operation an additional cost impact for maintenance and launch compared to the others. The solid-state laser is assed here advantageous, but lacking in bad beam quality and specific mass to power ratio, which are driving criteria for SPS applied laser systems. A most likely candidate is the direct solar pumped laser, which has less priority concerning system scaling and beam quality. But this system is a new technology area, thus much more detailed research work is needed here. Especially, the principle of direct sunlight pumping the laser, thus avoiding any solar arrays in space makes the enormous advantage of such a system.

Table 24. Candidate Laser Systems Comparison

| Laser Characteristics | Solid State Laser | Chemical Laser | Direct Solar Pumped |
|-----------------------|-------------------|----------------|---------------------|
| Efficiency            | ++-               | ++-            | ---                 |
| Opt / opt             | +++               | /              | /                   |
| El / Opt              | ++-               | /              | /                   |
| Specific Mass (kg/fW) | ++-               | ++-            | ++-                 |
| Performance Scaling   | ++-               | +++            | ++-                 |
| Beam Quality          | +++               | ++-            | ++-                 |
| Wave Length           | ++-               | ++-            | ++-                 |

Summarizing out of this actual assessment, the solid-state laser types represents the most promising selection for a future application.

- **Power Transmission Critical Technologies**

Due to their overall impact on the SPS system mass and cost the most critical technologies are:

- o Solar Power Generation (stretched lens array, rainbow array, thin film PV, quantum dot, Brayton Cycle Solar Dynamic)
- o Power Management and Distribution (DC-DC conversion, DC-AC-DC conversion LT/HT super conductor)
- o Wireless Power Transmission (Laser type, magnetron, klystron)
- o High effective thermal control
- o Large, lightweight self-deployable structures and dynamic structure control
- o In-orbit transportation (reusable and semi-reusable systems)
- o Power re-conversion on earth (PV, solar thermal)
- o High efficient long distance power transmission on ground (HVDC)

### 3.4 Solar power plant design data - reference system

#### 3.4.1 Basic assumptions

For the evaluation of a combined SPS/terrestrial solar power system the assumptions of work, which have been agreed in common understanding within the study team, are:

- o System represents a 2030/50 technology status including development sensitivity
- o Continuous power to users on ground
- o Ground PV reception facility enables superposing of natural sunlight and laser power beam by SPS (multiple)
- o Solar Power Plants in orbit concept covering a 'dual' energy supply:
  - o 'space-based' solution with terrestrial optimized receiver
  - o combined solution with natural sunlight plus superposing with multiple SPS load curve for base load and remaining load (additional storage capability)
- o System lifetime thirty years for a single power platform in space GEO orbit
- o Implementation time for a single unit in GEO about two years

- o Development of dedicated semi-reusable space transportation system assumed
- o Laser technology is preferred versus microwave concerning distinct criteria, but both microwave and laser technologies have been assessed:
  - o transmission elements size
  - o side-lobes/spikes issue
  - o negative impacts of MW (navigation, communication, human / environment) laser modular implementation

Typical seasonal characteristics of pure terrestrial and combined Solar Power Systems are given in Figure 10 (example from previous EADS company investigations and not representing the actual study data).

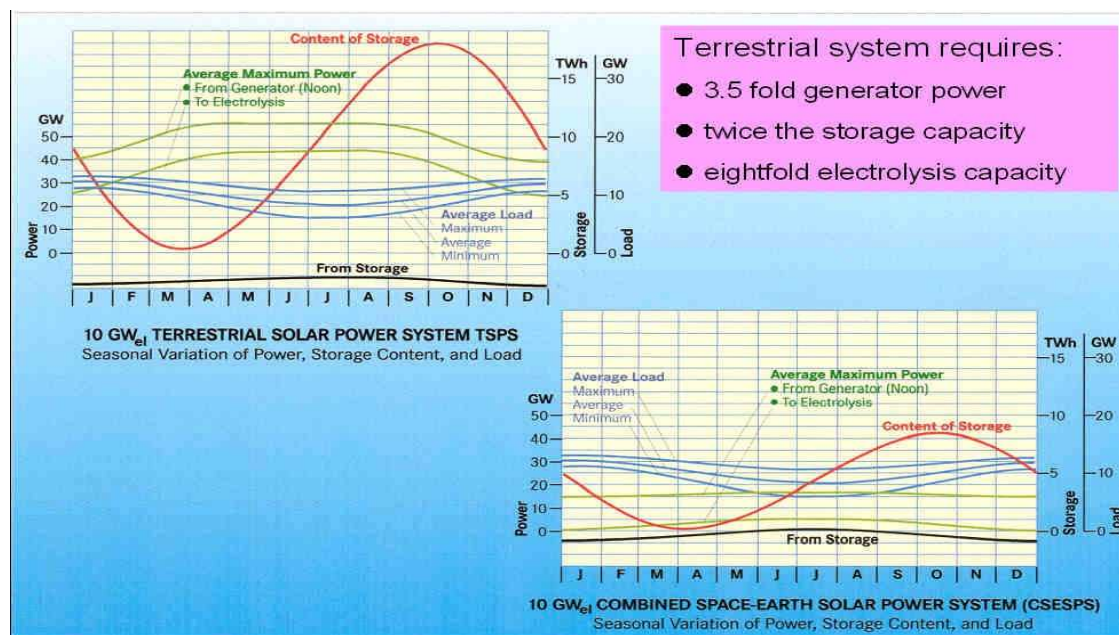


Figure 10. SPS Seasonal Variations of Performance (Example)

A reference overall SPS scenario is pictured in Figure 11 and Figure 12. They show one element of a SPS power platform in GEO. This facility with a diameter of 12 km is taken as reference for this study and provides two laser based power transmission elements. These systems are part of a concept, which involves the man and EVA for orbital work like maintenance. Recent study activities assess reduced involvement of humans in space to minimise risks and costs. The built-up and implementation in space for this example is assumed to be over 30 years. It shall be pointed out, that this scenario represents a long-term perspective, whereas for the actual study work here the solar power system as in Figure 12 was applied for the calculation model.

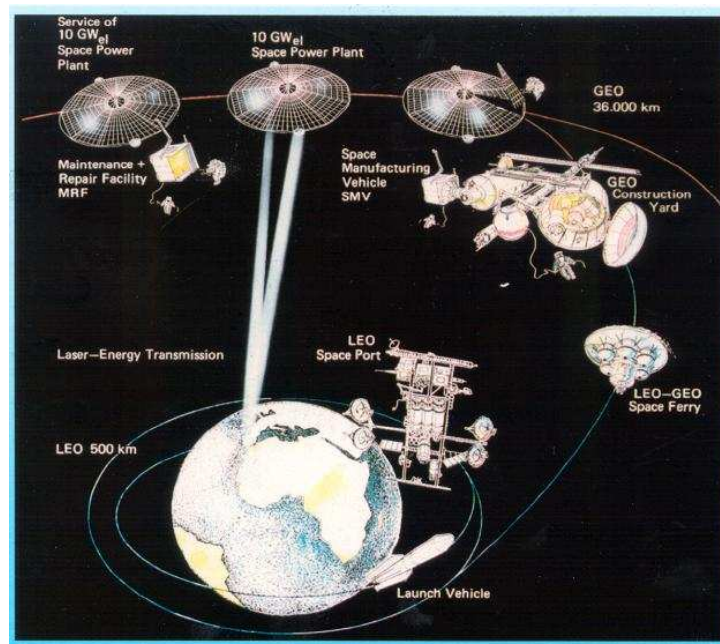


Figure 11.SPS GEO Potential Scenario

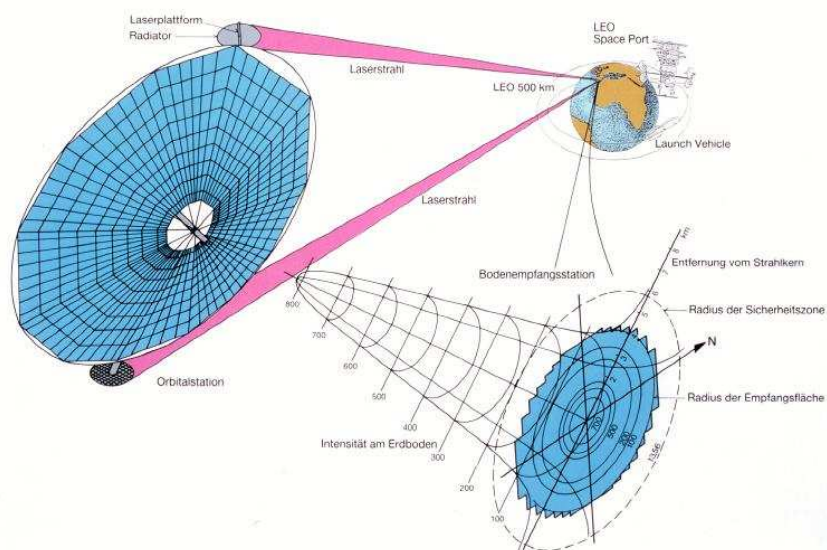


Figure 12. SPS Power Platform in GEO

The main Solar Power Infrastructure Scenario elements in space are (see figure 11) listed below.

- o SPS in GEO
  - o Solar disk configuration
  - o Planar concentration ( $CF \approx 2$ )
  - o Spoke-wheel structure
  - o Laser Power Transmission
- o Construction Yard in GEO (not reference for this study)
  - o Sheltered Habitats

- o Robotic assembly facility
- o Interorbital Tug & Ferry Fleet (not reference for this study)
  - o Cargo Tugs electrically driven
  - o Ferries chemically propelled
- o Spaceport in LEO (not reference for this study)
  - o Hosting of space-workers
  - o Propellant loading facility
- o ETO Transportation System
  - o RLVs for „Space-workers“
  - o HLLVs for upload cargo

(combining partial reusability with in-orbit re-utilisation)

### **3.4.2 Solar power reference system design data**

- **Potential Orbital Scenario Comparison**

The investigation of solar power systems provides, besides the technology issues itself, also considerations of the operational orbits. In principle, the LEO, Molnyia or Loopus-type, sun synchronous and GEO are the alternatives. In table 5, the relevant characteristics, as contact times and daily contact times are addressed; possible implications on laser versus microwave application are added.

The basic criteria for the selection of operational orbit for SPS are

- o orbit parameter and orbit stability
- o average solar radiation intensity per day
- o orbital frequency/thermal cycling
- o gravity gradient forces
- o ground contact times/daily ground contact times

- **Crude Comparison between 400 km LEO and GEO SPS in LEO**

A dedicated assessment of the LEO versus the GEO is given; the LEO has

- o 60 percent the average daily solar insolation:  
( $\approx 20 \text{ [kWh/(m}^2 \times \text{day)]}$  in LEO against  $\approx 33 \text{ [kWh/(m}^2 \times \text{day)]}$  in GEO)
- o 15.6 times higher orbital frequency and (thermal) cycling  
( $1.13186E-03 \text{ [sec-1]}$  in LEO against  $7.27221E-05 \text{ [sec-1]}$  in GEO)
- o 242 times higher gravity gradient forces  
(Differential acceleration at 1 km radial distance from centre of gravity:  
 $3.84332E-03 \text{ [m/sec}^2\text{/km]}$  in LEO against  $1.58655E-05 \text{ [m/sec}^2\text{/km]}$  in GEO)

A need for relay stations in LEO due to short contact times with ground stations arises; therefore the conclusion is, that the GEO is the better choice

Table 25. SPS Operational Orbits Overview

| Space Solar Power Concepts Orbit Options | Characteristics                                                                                                                                                                                                                                                                                                                                                                                                               | Contact times                                                                                                                                     | Average Daily Contact Times                                                                                                                                                                                                                                               | Laser / Mw Applicability Consequences                                                                                                                                                                   |
|------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| GEO                                      | <ul style="list-style-type: none"> <li>o 36.000 km / 0 degree inclination</li> <li>o Quasi-continuous insolation</li> <li>o Low gravity gradient forces/moments</li> <li>o Low orbit frequency / thermal cycles</li> <li>o Continuous contact with ground</li> <li>o Most efficient util. of equipment</li> <li>o More hostile env. / very long WPT distance</li> </ul>                                                       | <ul style="list-style-type: none"> <li>o 24 hrs duration</li> <li>o 98% sunlight, max.2 hrs duration of eclipse phases around solstice</li> </ul> | <ul style="list-style-type: none"> <li>o Average 24 hrs</li> </ul>                                                                                                                                                                                                        | <ul style="list-style-type: none"> <li>o Transmitting apert. size for MW by fa. 100 more comp. to laser needs</li> <li>o Laser fac. as high modular systems</li> <li>o MW side spikes of GND</li> </ul> |
| MOLNYIA                                  | <ul style="list-style-type: none"> <li>o LOOPUS-constellat of 3/5 satellites</li> <li>o Resulting quasi-stationary GND contact / contacts into valleys</li> <li>o 5-5 sats constellation allows a flexible load supply</li> </ul>                                                                                                                                                                                             | <ul style="list-style-type: none"> <li>o 1, 3, 5 –12 hrs depending on constellation (quasi continuous)</li> </ul>                                 | <ul style="list-style-type: none"> <li>o Quasi continuous with 3-5 sats on 1200/39.000 km and 1.000/41.000 km orbits for GND sat.</li> </ul>                                                                                                                              | <ul style="list-style-type: none"> <li>o multiple sats with small laser apert.</li> <li>o Phased beam steering</li> <li>o MW spikes</li> </ul>                                                          |
| LEO                                      | <ul style="list-style-type: none"> <li>o 800-1000 km / 51 degree inclination</li> <li>o Better accessibility by SSTO</li> <li>o Benign radiation environment</li> <li>o ‘Short’ distance for WPT</li> <li>o Intermediate GND contact/ pronoun. eclipse phases</li> <li>o Reduced average isolation</li> <li>o Much higher sever thermal cycling / orbital cycling, drag propellant demand, gravity gradient forces</li> </ul> | <ul style="list-style-type: none"> <li>o 92 min orbit duration</li> <li>o 39% (36 min) eclipse phase</li> <li>o Typical 10 min contact</li> </ul> | <p><u>Case 1:</u></p> <ul style="list-style-type: none"> <li>o 400/400 km-51.6 deg (Masp/Madr/Bre/Kiru - 16/28/24/0)</li> </ul> <p><u>Case 2:</u></p> <ul style="list-style-type: none"> <li>o 1000/1000 km-51.6 deg (Masp/Madr/Bre/Kiru - 54/73/61/23 min)</li> </ul>    | <ul style="list-style-type: none"> <li>o Beam steering to GND target phased array technology \</li> <li>o Aperture size impacts</li> </ul>                                                              |
| Sun-synchronous                          | <ul style="list-style-type: none"> <li>o 700 – 1100</li> <li>o 98 degree inclination</li> </ul>                                                                                                                                                                                                                                                                                                                               | <ul style="list-style-type: none"> <li>o Average 8 min/orbit</li> <li>o Continuous sun orientation</li> </ul>                                     | <p><u>Case 1:</u></p> <ul style="list-style-type: none"> <li>o 700/700 km-98.2 deg (Masp/Madr/Bre/Kiru- 25/29/38/73)</li> </ul> <p><u>Case 2:</u></p> <ul style="list-style-type: none"> <li>o 1400/1400 km-101.4 deg (Masp/Madr/Bre/Kiru - 57/69/101/135 min)</li> </ul> | <ul style="list-style-type: none"> <li>o Beam steering to GND target / phased array technology</li> <li>o Aperture size impacts</li> </ul>                                                              |

- Orbit Assessment Suitable for SPS

Typical SPS orbits have been assessed in detail for different inclinations and orbital altitudes. Excerpts are given hereafter, whereas the complete assessment is attached to this report. For the ground station, example sides in Europe, distributed over the latitude, has been taken as comparison.

### Sun-Synchronous Orbits

Analyses done for: Sat-1: H = 700 / 700 km, i = 98,2° (sun-sync.)

Sat-2: H = 1400 / 1400 km, i = 101,4° (sun-sync.)

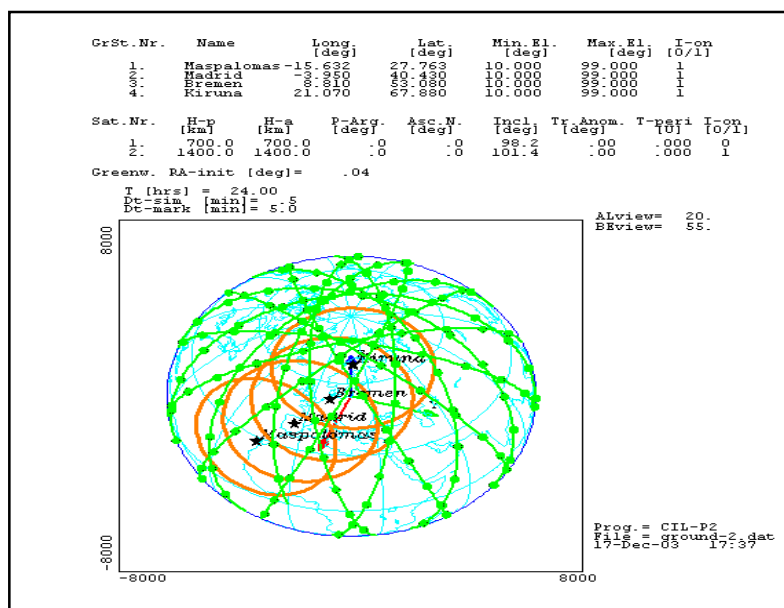


Figure 13. Ground Track Projections

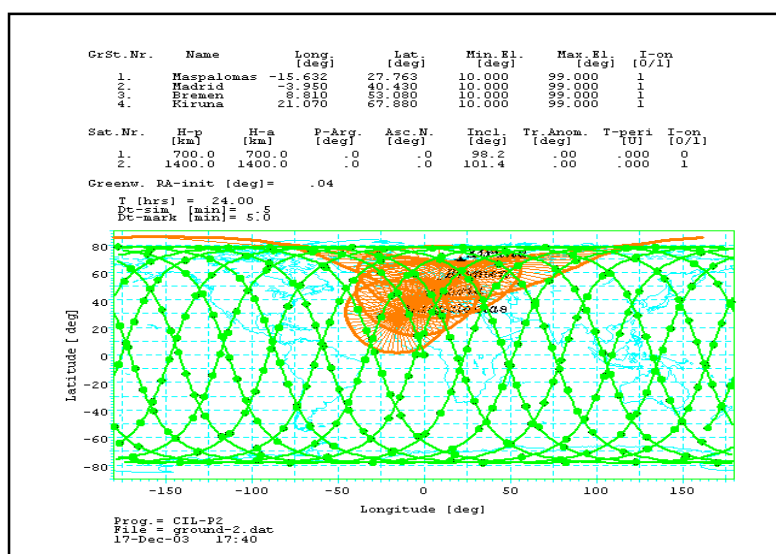


Figure 14. Ground Track Projections

Remarks:

|           |   |                                        |
|-----------|---|----------------------------------------|
| ELmin     | = | Elevation at local horizon             |
| Tsum      | = | Total contact time in 10 days          |
| Tsum / 10 | = | Average contact time in 1 day          |
| N         | = | No. contacts in 10 days                |
| Taver     | = | Tsum / N = Average single-contact time |

- Molnyia-Orbits

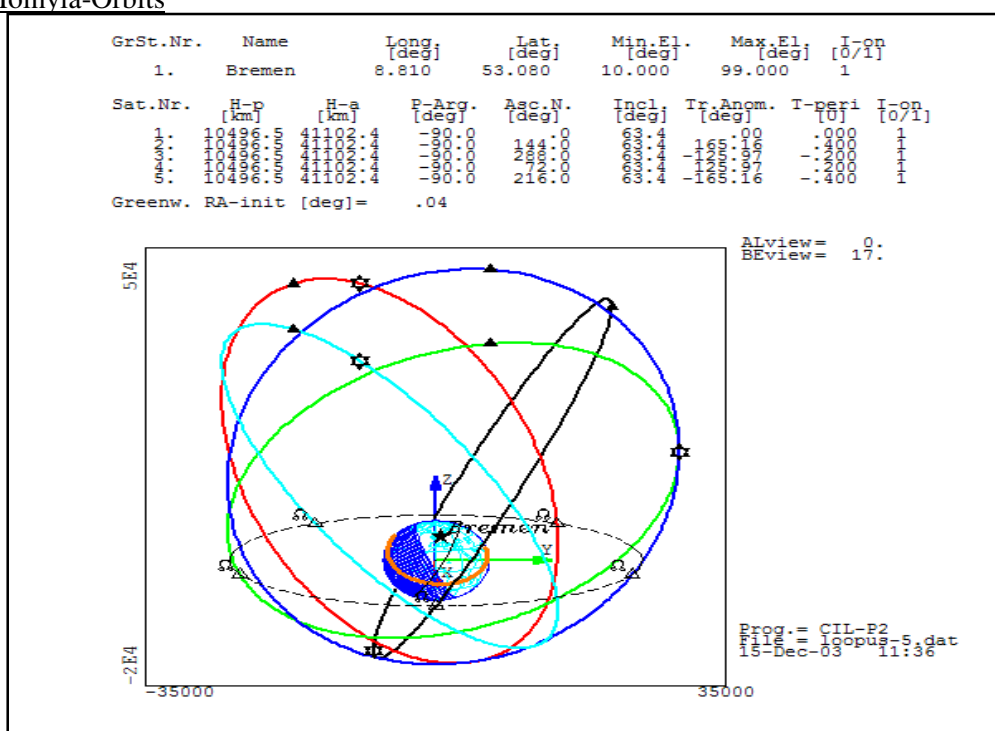


Figure 15. LOOPUS constellation of 5 satellites/Inertial view (geocentric, equatorial) perspective 'flat' on equator plane



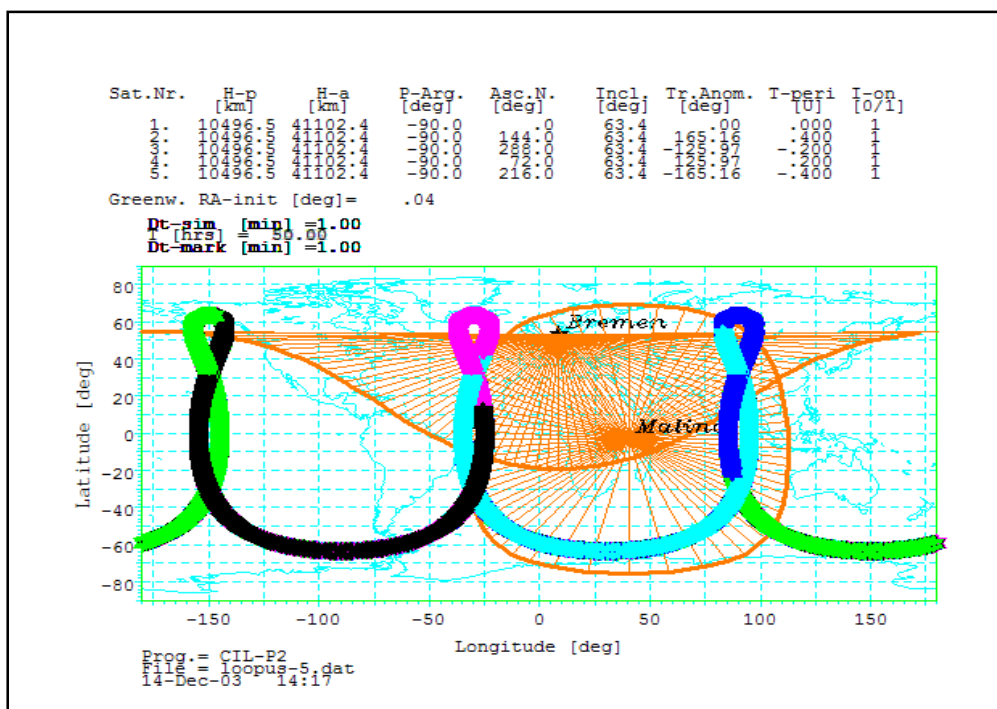


Figure 16. LOOPUS-constellation of 5 satellites/Groundtrack with 3 geostationary loops  
On the northern hemisphere

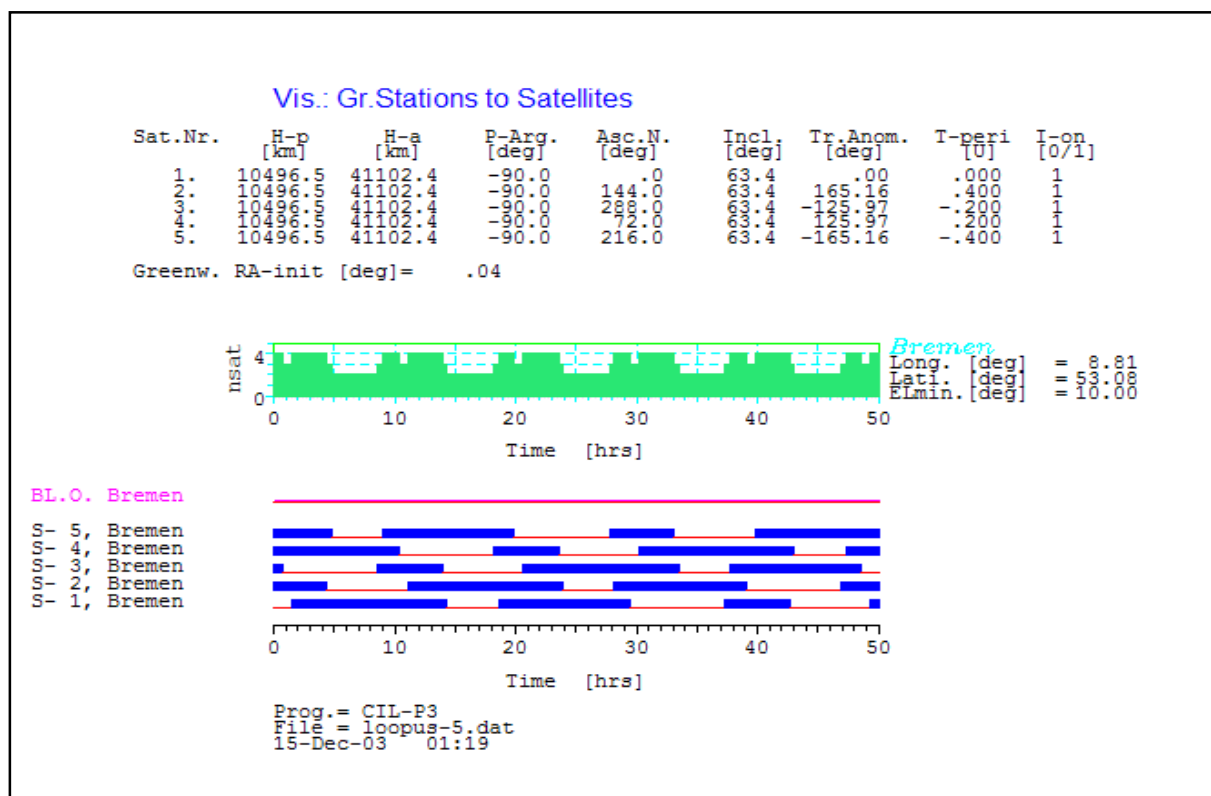


Figure 17. LOOPUS-constellation of 5 satellites/Contact times to Bremen GND station  
quasi-stationary contact to GND station

The evaluation of contact time showed, that concerning Molnyia-type orbits, a quasi continuous contact to the selected ground site is provided with 3 or 5 satellites in orbit.

This evaluation of the EADS SPS reference concept for these orbits turned out, that

- o Geostationary has continuous contact
- o Low earth orbit has intermediate contact/~16 – 73 min/day
- o Loopus-types has continuous contact/3-5 satellites operation
- o Sun-synchronous has 25 – 135 min/day

As a resume, it can be stated that the GEO seems to be the best suited orbit for the combined SPS solution, although the Loopus-type orbits provide also continuous ground coverage of selected station, but they provide disadvantages due to their high elliptical shape, thus passing frequently radiation belts; despite the fact that the very large SPS has to operate within the related elliptical velocity conditions.

### 3.4.3 Combined space-ground solar PV power system

- Combined System Concept

The conception of a regional energy supply system based on power from space requires the optimal accessibility to the user electricity grid. Depending on the locality of such a regional system the energy transfer from the solar power reception site to the destination may require a bridging of large distances. In order to avoid the related losses a 'direct' access to the user could be applied by using a regional stratospheric platform. An overview of potential elements of such a system is given below in the Figure 18.

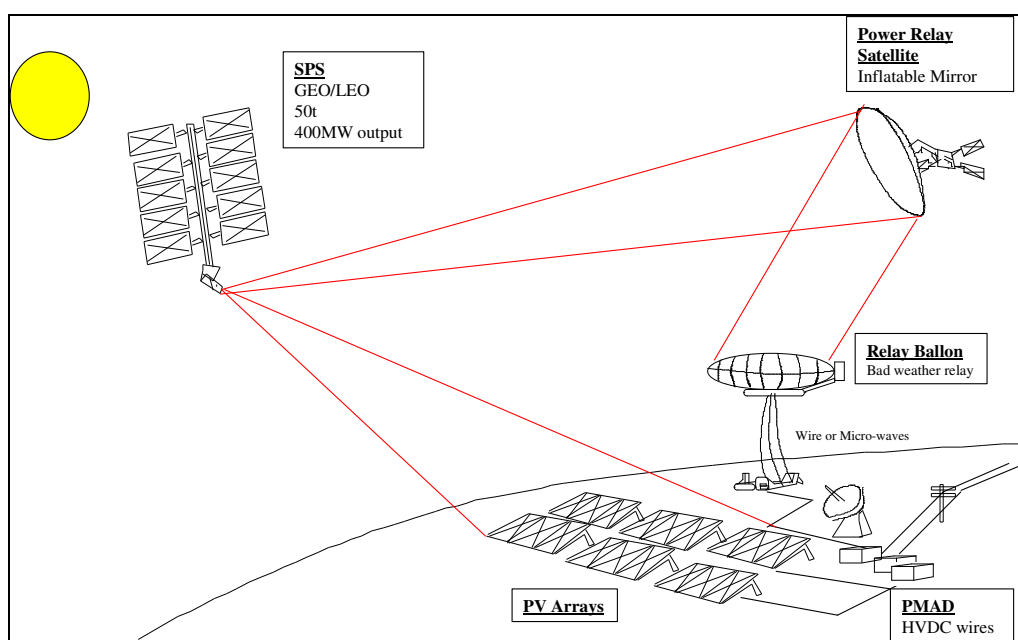


Figure 18. Typical SPS Scenario Elements and Example Data

In the frame of the SPS study the main elements blocks, which have been investigated are:

- the space segment composed of an SPS
- the ground segment made of ground reception stations and I/F with local or remote electricity grids
- the ground element also comprises elements for local energy storage and transportation based on hydrogen processing and HVDC-lines.

Thereby, as previously stated within the study proposal, a reference to the EU FP ESSPERANS project outcomes on energy processing solutions, could not be made, due to the fact that the proposal campaign led not to an initiation of a project.

For the run of the actual EU 6th FP campaign in 2004, a new and revised proposal is intended for submission.

The ESSPERANS project is aiming to establish the science, technology and social feasibility roadmap, and to develop the knowledge basis and enabling technologies, as well as the European and international socio-political and economic co-operation schemes, for the intensive use of solar energy for electricity and hydrogen generation, combining Very Large Scale Solar Energy Platforms on Earth and Space, as a global, clean, renewable, therefore sustainable, energy production scenario.

Several ways for immediate and CO<sub>2</sub> neutral hydrogen generation technologies are envisaged, such as the technology of photo-catalytic hydrogen generation from water. The solar energy collected on a very large scale could then be used for totally CO<sub>2</sub> neutral electricity production and hydrogen generation through water splitting by using several processes, including electrolysis but also photo catalysis and laser photolysis of water. Direct solar energy pumped laser radiation, for example, could be used for hydrogen generation through laser photolysis of water, which is the most direct route from solar energy to clean, renewable and abundant hydrogen.

A typical example is a solar power reception system coupled with a H<sub>2</sub> production facility (water electrolysis), H<sub>2</sub> storage facilities and fuel cells.

The conception of a regional energy supply system, located e.g. in central /south Europe led to the assessment of system parameters like,

- energy demand projection of electricity
- the energy supply scenario case, as base-load, peak-load supply, and the related daily, seasonal energy demand characteristics
- the selection of the optimal orbit LEO, MEO or GEO; e.g. as sun-synchronous, Molnyia type orbits
- the ground reception facilities sizing
- the hydrogen generating and treating systems
- the transportation elements to connect the complete 'SPS-plant' with the existing energy / electricity grid

Furthermore, sensitivity assessments have been made for the characteristics:

- operation orbit selection
- power level of SPS in orbit

- supply case, base- and peak-load storage needs, day and night cycles
- basic system characteristics as in-orbit SPS mass, lifetime, maintenance, launch cost, operational cost in-orbit and on ground

In Figure 19 a morphology for Solar power ground receiving facility concepts are depicted.

The case for laser and microwave alternatives is made here, whereas emphasis was laid on laser systems for power transmission, but microwave technology was also analysed. The candidate types are laser diode arrays (MOPA principle), diode pumped solid state, direct solar pumped solid laser and as a further potential candidate the free electron laser.

The ground reception site is characterized by the alternatives of extra concentrating solar dynamic concentrators oriented to the SPS, fixed tilted to latitude, of the extra concentrating photovoltaic concentrators orientated to the SPS with fixed tilted to latitude and of the planar photovoltaic arrays, using natural sunlight and power from space.

The latter was taken here as case for deeper analysis, and this concept uses existing photovoltaic modules inclined to the latitude and oriented in East-West direction.

A microwave concept would need a rectenna on ground, with this receiving element lying flat on ground or being modular inclined to the latitude. In a combined scenario an extra ground photovoltaic array or solar dynamic receiver would be needed.

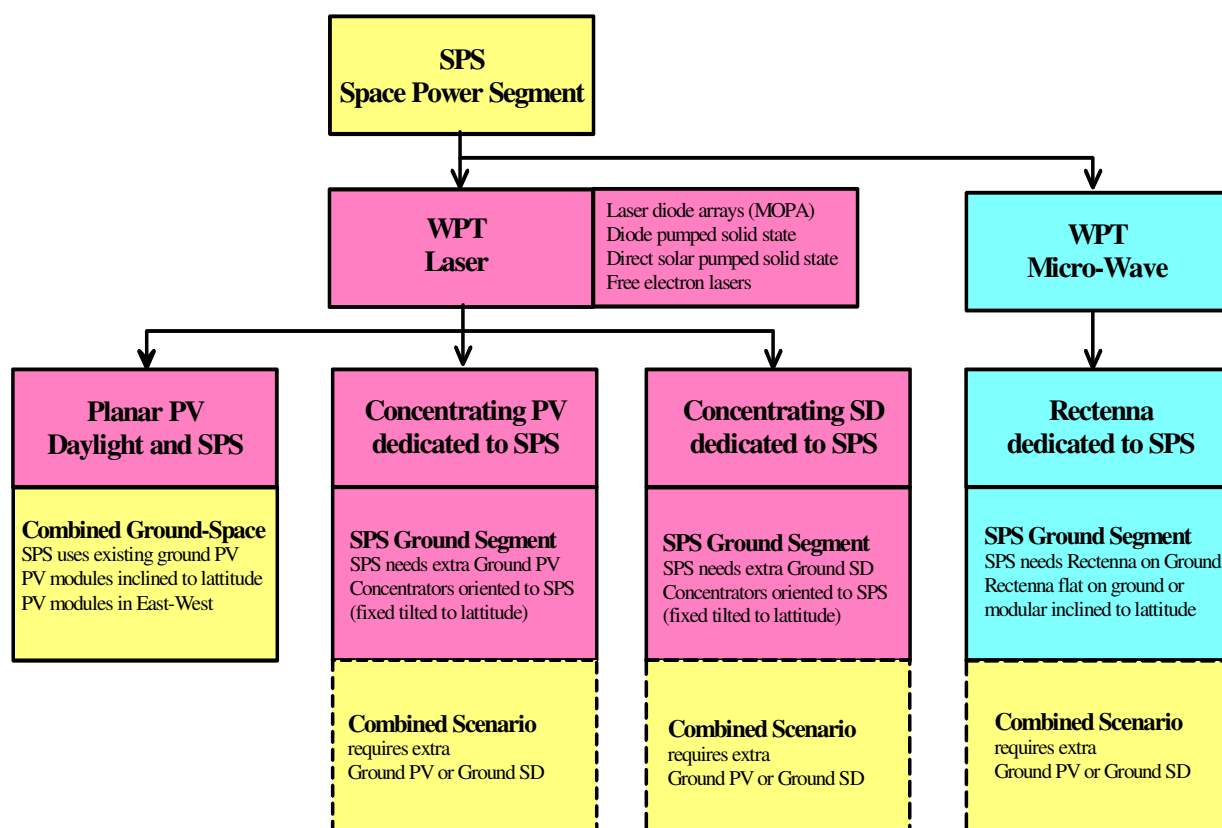


Figure 19. Morphology of SPS Concepts Investigation Alternatives

The study work was based on the following assumptions, which were agreed upon during the workshop 1 with the customer and the study team members:

- **Basic Assumptions**

The assumptions for the SPS study for the space sector are based on the concept of a combined use of photovoltaic cells for both the natural solar radiation and laser radiation from space, as outlined in the previous chapter. This scenario applies assumptions on the timeframe of 2020/2030 for the technologies.

The following harmonisation with terrestrial PV systems has been agreed on:

Supply Zone: A3 (South Egypt: Aswan and El Kharga)  
9.5 kWh/day DNI in March & September

**PV Power Generation:**

- o Basic Assumption: Cell technology maturity level for SPS identical with technology for ground PV
- o Specific power: 1125 W<sub>peak</sub>/kg (thin film cells @ STC)
- o Specific cost: 4500 €/kW<sub>peak</sub> @ STC and starting point 2 GW
- o Learning factor: 0.8 starting at 2 GW up to 500 GW; 0.92 above 500 GW production
- o Efficiency: 20 % for daylight @ STC (AM1; 1000 W/m<sup>2</sup>; 28°C); 50 % for laser illumination
- o Loss factor: 5% on ground (soiling, etc); 0.6%/year aging/degradation (SPS & ground)
- o O&M cost: 1.5 %/year of investment on ground; 0.6 %/year of investment in space
- o PV cells on ground adapted to later laser illumination from space
- o PV illumination on ground: AM1 daylight  $\leq 1000 \text{ W/m}^2$  + laser  $\leq m \times 820 \text{ W/m}^2$
- o PV illumination in space  $\geq 1.9 \times 1257.3 \text{ W/m}^2$  (AM0) using planar concentrator foils

**Ground Transmission:**

- o Average Transmission distance: 5000 km
- o Type: 800 kV HV DC double dipole
- o Capacity: 6.5 GW per line

Transmission losses:

- o HVDC stations:  $2 \times 0.5\% = 1\%$
- o HVDC lines: 2.5 %/1000 km

Investment per 6.5 GW capacity:

- o HVDC stations:  $2 \times .35 \text{ B€} = 0.7 \text{ B€}$
- o HVDC lines: 0.3 B€/1000 km
- o Progression ratio: 0.96 starting at 10,000 km
- o O&M cost: 1 % of investment p.a.

### Pumped Hydroelectric Storage:

- o Efficiency: 0.85  
(in/out neglecting evaporation from storage basins)
- o Specific investment:
  - Hydro storage: 0.012 B€/GWh
  - Hydro power blocks: 0.600 B€/GW
  - O&M cost: 4E-6 B€/GWh
- o Land Demand:
  - SPS Ground PV Site: 116.4 – 216.8 [km<sup>2</sup>] for 1 to 3 SPS
  - HVDC Transmission Lines: 230 [km<sup>2</sup>/(10 GW)] per 5000 km
- o Land Cost:
  - SPS Ground PV site: 2 [€/m<sup>2</sup>]
  - HVDC Transmission Lines Area: 10 [€/m<sup>2</sup>]
- o Financing:
  - Duration: 50 % of 1 year construction period per SPS at
  - Interest rate: 6 [% per year]
  - Relative Financing Cost: 5.4 % of construction cost

The transport into space is one of the main technical and economical barriers to the implementation of solar power systems. In this study the Space Transportation Top Level Requirements are taken for the SPS reference scenario as presented in the beginning.

The SPS demands Launch Vehicles (LV) capable of:

- o High launch frequency (up to 10,000 launches per year depending on vehicle's payload capability)
- o Using environmentally benign propellants
- o Using known technologies
- o Mass production of single use items (tank & payload shells, etc)
- o Return of reusable stages / items to the launch site

The vehicle concepts considered in this study are:

- o **Ariane 5+** currently under development; further improvements for SPS possible and necessary, but will not meet / underbid ADLER or Hopper. Solid rocket boosters to be replaced by reusable liquid boosters to reduce cost and burden on the environment.
- o **ADLER** LV designed especially for large scale SPS scenario, based on known existing technologies. Combines reuse of expensive items and in-orbit reutilisation.
- o **Hopper** LV studied, pre-designed, and analysed in the German ASTRA programme using known technologies (concept adapted from ESA's previous FESTIP System Study).

Further evolution to "Once-Around Earth" for SPS are considered possible and desired, they will reduce cost & enhance operations. Reusable Heavy Lift Launch Vehicles, such as NEPTUN, are considered in other studies and will also meet the cost goals for SPS.

Table 26. Reference Future Reusable Launcher System

| <b>Space Transportation:<br/>Vehicle</b>           | <b>ADLER</b>                | <b>Ariane 5+</b>        | <b>Hopper+</b>        |
|----------------------------------------------------|-----------------------------|-------------------------|-----------------------|
| Type                                               | Reuse & IO<br>reutilisation | expandable              | Semi-reusable         |
| Payload per launch: Net P/L in<br>GEO per Launch   | 62.5 Mg LEO<br>45.4 MG      | 12.56 Mg GTO<br>10.2 Mg | 10.5 Mg GTO<br>8.5 Mg |
| Cost per Launch to LEO:<br>starting with launch no | 51 M€<br>17                 | 130 M€<br>30            | 60 M€<br>4            |
| Learning factor                                    | 0.89                        | 0.92                    | 0.81                  |
| Flight per SPS                                     | 1780                        | 10330                   | 12050                 |
| First SPS transportation cost                      | 30.8 B€                     | 544.9 B€                | 43.85 B€              |
| Av. Specific transportation cost                   | 383 €/kg                    | 5118 €/kg               | 416 €/kg              |
| O&M re-flight                                      | 0.6% p.a.                   | 0.6% p.a.               | 0.6% p.a.             |

Please note to Table 26:

- o LEO to GEO transportation cost included in first SPS transportation cost.
- o Electric transfer propulsion assumed for LEO/GEO (ADLER), resp. GTO/GEO (Ariane 5+ and Hopper+)

In the Figure 20, Figure 21, and Figure 22 future reusable launcher systems are shown as they are currently under consideration for this study, and basically elaborated at EADS-ST in the case of the Phoenix and Hopper systems.



Figure 20. Future Adler Launcher Concept



Figure 21. Phoenix Reusable System



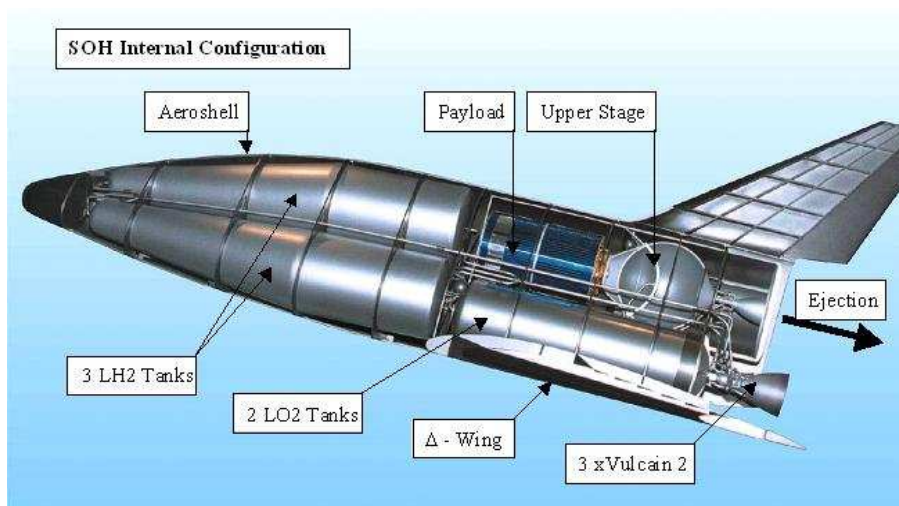


Figure 22. Hopper Reusable system

The evolution of SPS average and specific transportation costs are shown in the following Figure 23 and Figure 24, based on the values Table 26.

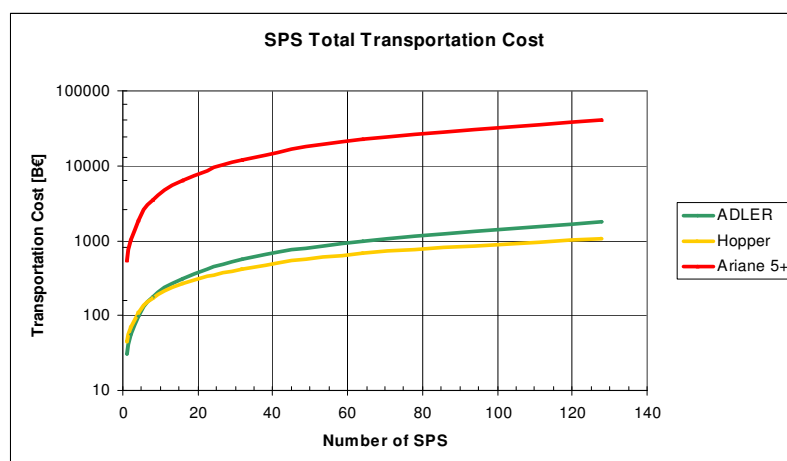


Figure 23. SPS Total Transportation Cost

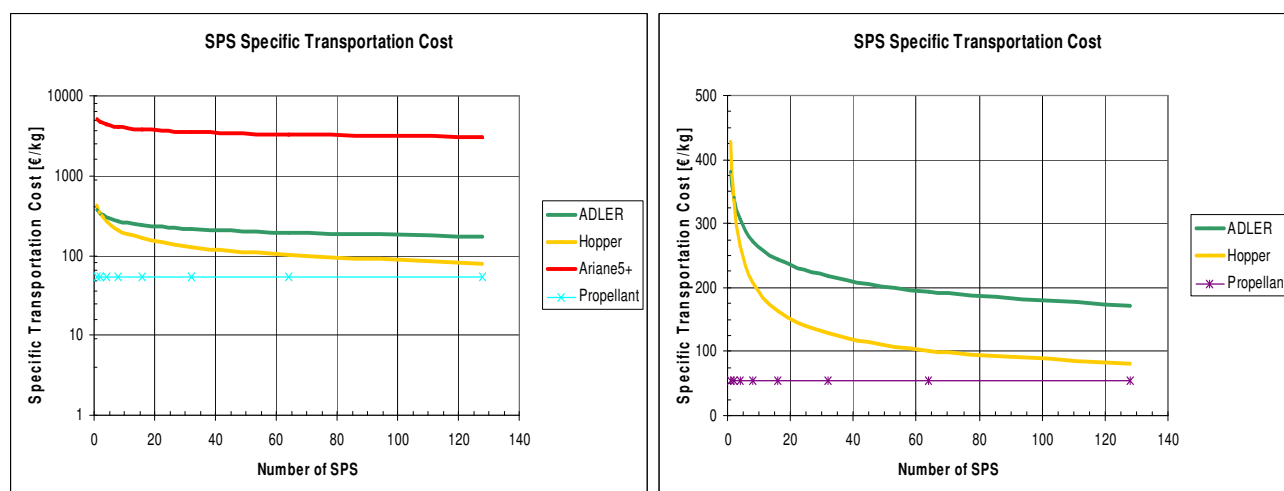


Figure 24. Evolution of SPS Specific Transportation Cost

From this assessment it can be concluded that the Ariane 5 type conventional expendable launch vehicles is economically and technically not acceptable for SPS application as this type is too expensive and gives too much burden on the environment. On the other hand, the Hopper type reusable HTHL vehicles using a rail-guided propelled launch sled and ADLER type VTVL vehicles may meet the technical and environmental requirements and may reach specific transportation cost of below 200 €/kg.

- **Solar Power Implementation Strategies**

The typical implementation paths of solar systems are depicted in Figure 25. The implementation starts terrestrial PV power facilities and is later on combined with power from space, once the orbital segments are established. The diagram depicts the choice between a pure terrestrial approach or a combined space-ground system. In the pure terrestrial solution growth is achieved by continuous extension of solar photovoltaic reception areas, whereas in the combined case growth is achieved by a continuous enhancement of space radiation. Basic principle is in either case that initially the terrestrial photovoltaic receivers are installed and operated. The same PV-cells would then be used for space laser radiation and solar radiation, whereas the PV-cells provide a considerable enhanced efficiency (e.g. > 40%) for the part of the laser spectrum.

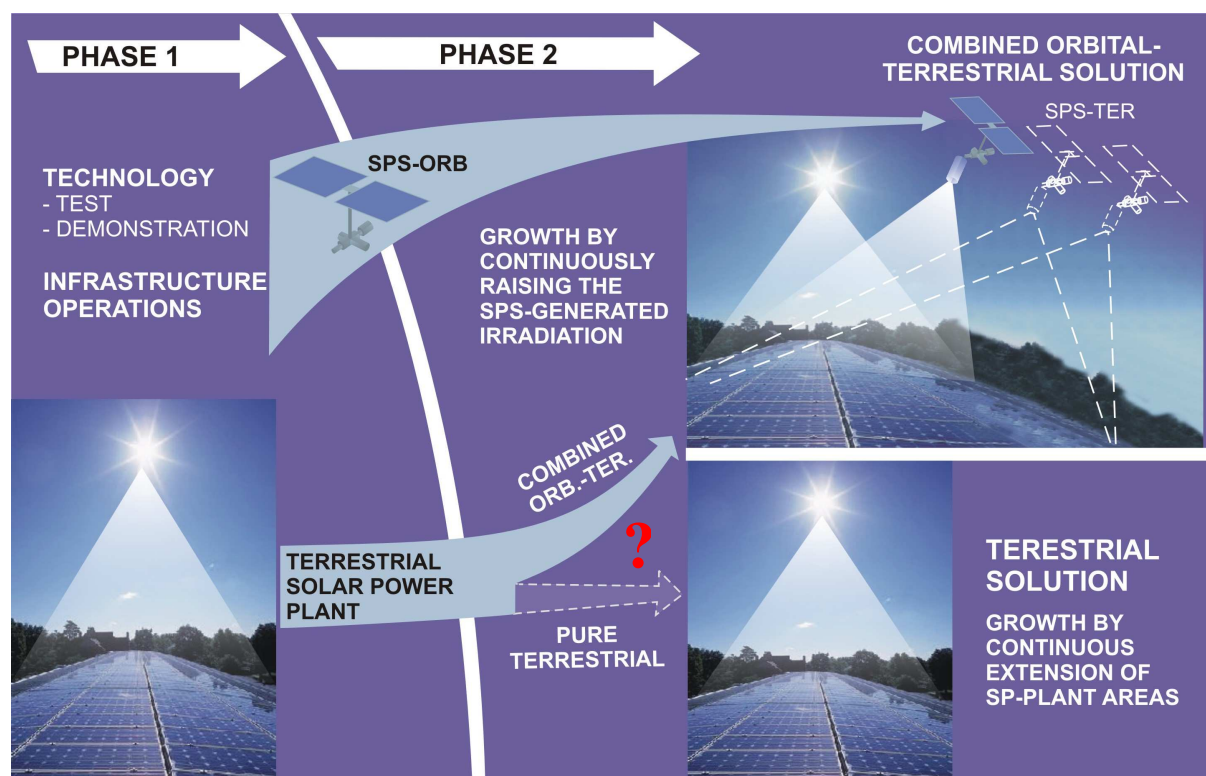


Figure 25. SPS implementation Rationale

- **Reference Scenarios Analyses**

Following the discussed approach, a complete power transmission chain analysis has been performed using the basic assumptions and boundary parameters as defined in the previous chapter. The power

chain investigations have been done for the microwave and laser transmission technologies. As mentioned earlier the laser transmission technology has been taken as the reference technology for deeper analysis, thus also addressing and calculating the ground reception photovoltaic plants. The working assumption, which also represents the basic idea of operation and implementation for a combined solar power system, is thereby to use the same PV solar cells and reception plants as the pure terrestrial system. This results in benefits in terms of system costs, and at least provides a gain in power generation due to the relatively high efficiency of the PV cells in the specific spectrum band of the laser (efficiency of 40% for a 532 nm laser).

In the following the transmission chain calculations are discussed for the laser and the microwave system type. Especially for both laser and microwave the following chains are addressed:

- o Efficiency and power chains (space segment)
- o Mass and cost data (space segment), and

For the laser technology the ground reception part is treated in more detail:

- o Efficiency and power chains (ground segment)
- o Mass and cost data (ground segment)
- o 25 GW combined space-ground system, with 3 power satellites
- o Beaming on one common ground plant

In the transmission chain block diagrams the difference between laser and microwave applications becomes clear. The microwave system requires for a pre-assumed 10 GW output on ground a considerable lower reception area and mass in space (e.g. a capture-total reception area 221,4 km<sup>2</sup> to 128,9 km<sup>2</sup> laser to microwave, A concentrator foil-reception area of the sunlight reflection/concentration mirrors/foils, APV array - active sunlight conversion area 110,7 km<sup>2</sup> to 64,45 km<sup>2</sup> laser to microwave; total mass: 126.300 Mg for the laser space segment and 63.190 Mg for the microwave space segment). This is caused by the better efficiency of the microwave system. The heat burden and the radiator area for microwave systems are therefore smaller (25,38 GW/16,45 km<sup>2</sup> waste heat/radiator area for laser, 9,455 GW/6,133 km<sup>2</sup> waste heat/radiator area for microwave). Also the transportation cost are lower (48B€ for laser and 25,9 B€ for microwave system).

The total space segment cost are for laser system 107,6 B€ and for microwave system 66,9 B€. The laser provides a 18,61 GW infrared laser beam power to ground, and the microwave 16,07 GW RF beam power to ground.

The assets of the laser system turn out on the ground, where a considerable smaller reception area is required (11,3 x 17,8 km<sup>2</sup> for microwave rectenna and 116,4 km<sup>2</sup> for laser reception plant). In addition, the overlay of the space laser radiation with the natural sunlight and as the basic principle, the overlay of the ground PV area with up to 3 SPS in space is advantageous over a microwave system, especially in the higher ground reception facilities cost (for 10 GW 'simple' PV reception plant with 2,56 GW sun light/7,44 GW laser by 51,6 B€, and for a 25 GW/3 SPS and 216,8 km<sup>2</sup> PV reception area by 66,0 B€). Nevertheless the transportation cost into space is one of the enabling cost drivers of the system. Furthermore, it should be pointed out, that the laser system enables a modular implementation approach in space; in this sense sub-units or modules of the later complete in-orbit SPS plant could brought into space sequently, on a terrestrial consumer demand driven basis, and be operated already and producing power to the terrestrial user grid. This modular approach is not possible with microwave technology, which requires that kind of integrated (complex mass) transmission systems in space. In the case of failure of a microwave subunit, the beam phasing is disturbed and terrestrial high

intensity spike and side lobe effects occur (harm to human, flora, fauna and RF ground use), which will not occur in the case of laser application.

For the SPS Space Segment Reference the results of the trades are given in the following diagrams.

In Figure 26, the efficiency and power chain elements and related contributions are depicted, based on the reference scenario. The assessments have been done for both the laser and microwave options. As the laser technology is taken as reference for the SPS more emphasis is put on this technology. A deeper analysis of the microwave option and a comparison in detail should be subject of a detailed system analysis.

In Figure 27, the mass and cost data of the contributor of the power chain are shown as comparison between laser and microwave.

For the SPS PV Ground Segment Reference the results Figure 28 shows the power chain and calculated efficiencies, Figure 29 shows the mass and cost data. Figure 30 shows the mass and cost data for combined space-terrestrial systems. For a total power outcome of 25 GW on ground, including hydrogen storage, with 2.56 GW average from daylight and 22.4 GW from IR laser light, the total cost are 66 B€, 55.8 B€ for construction and 10.2 for operation and maintenance.

# Efficiency and Power Chains

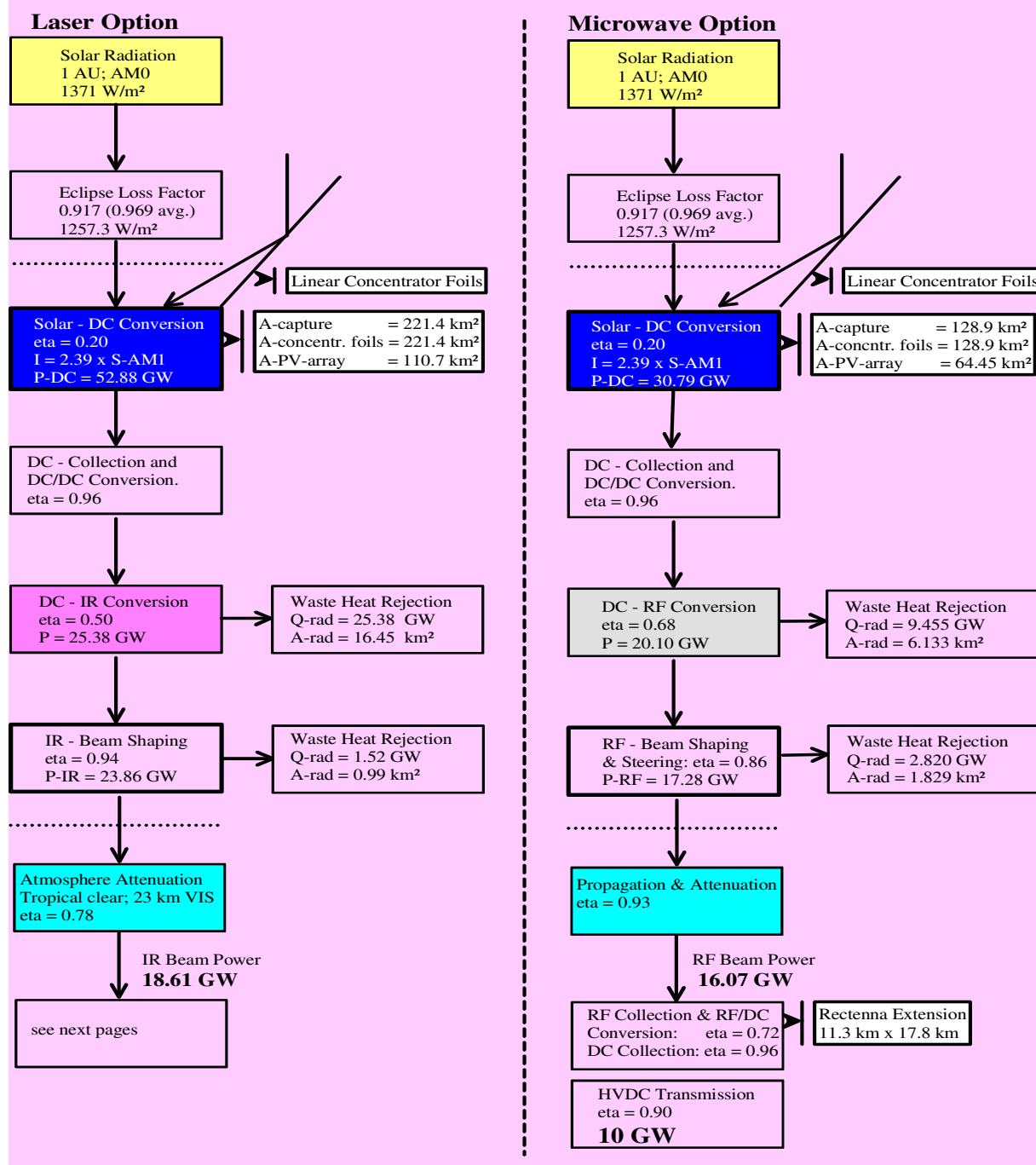


Figure 26. Efficiency and Power Chains for Laser and Microwave Systems in Space

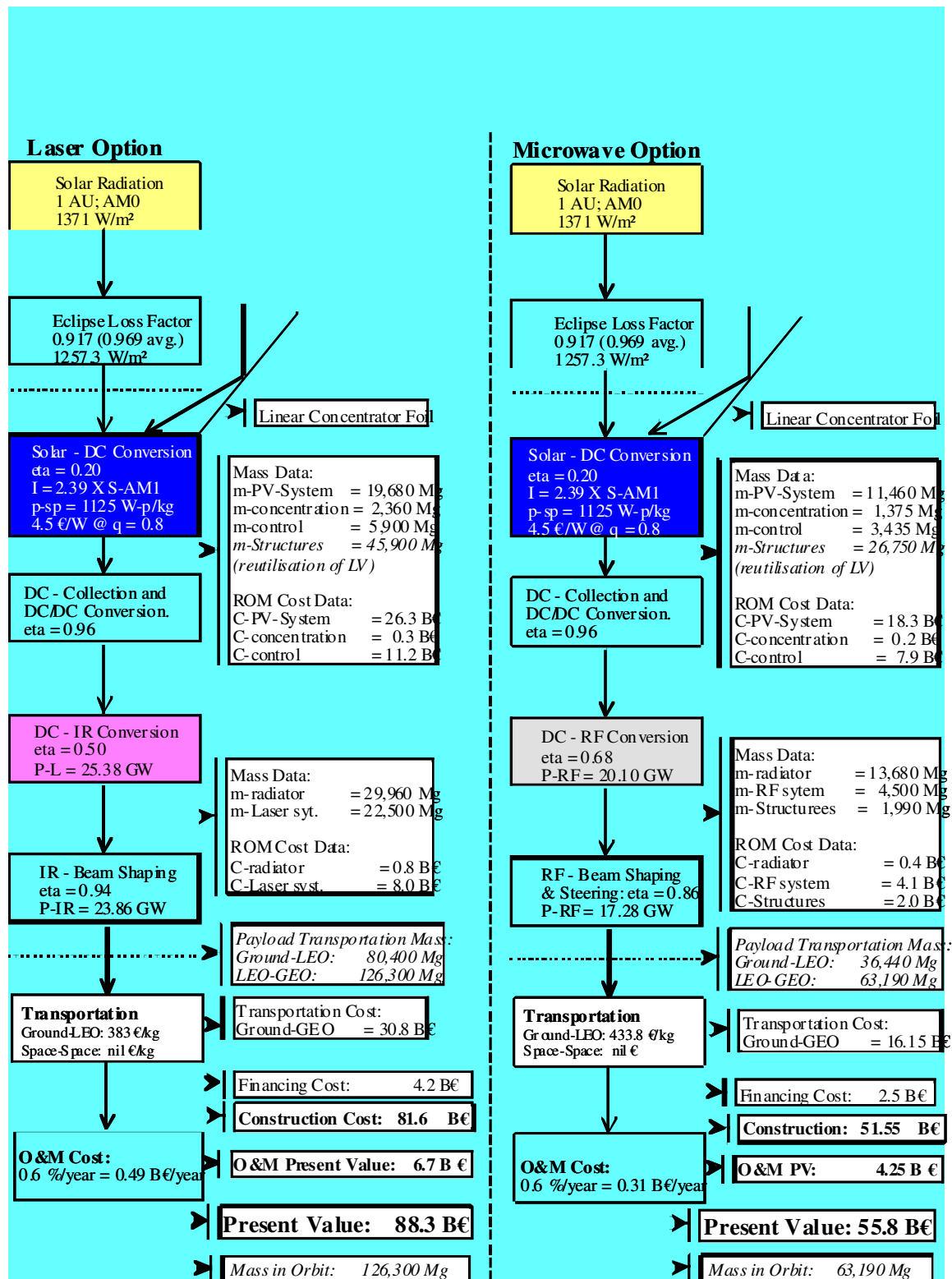


Figure 27. Mass and Cost Data for Laser and Microwave Systems in Space

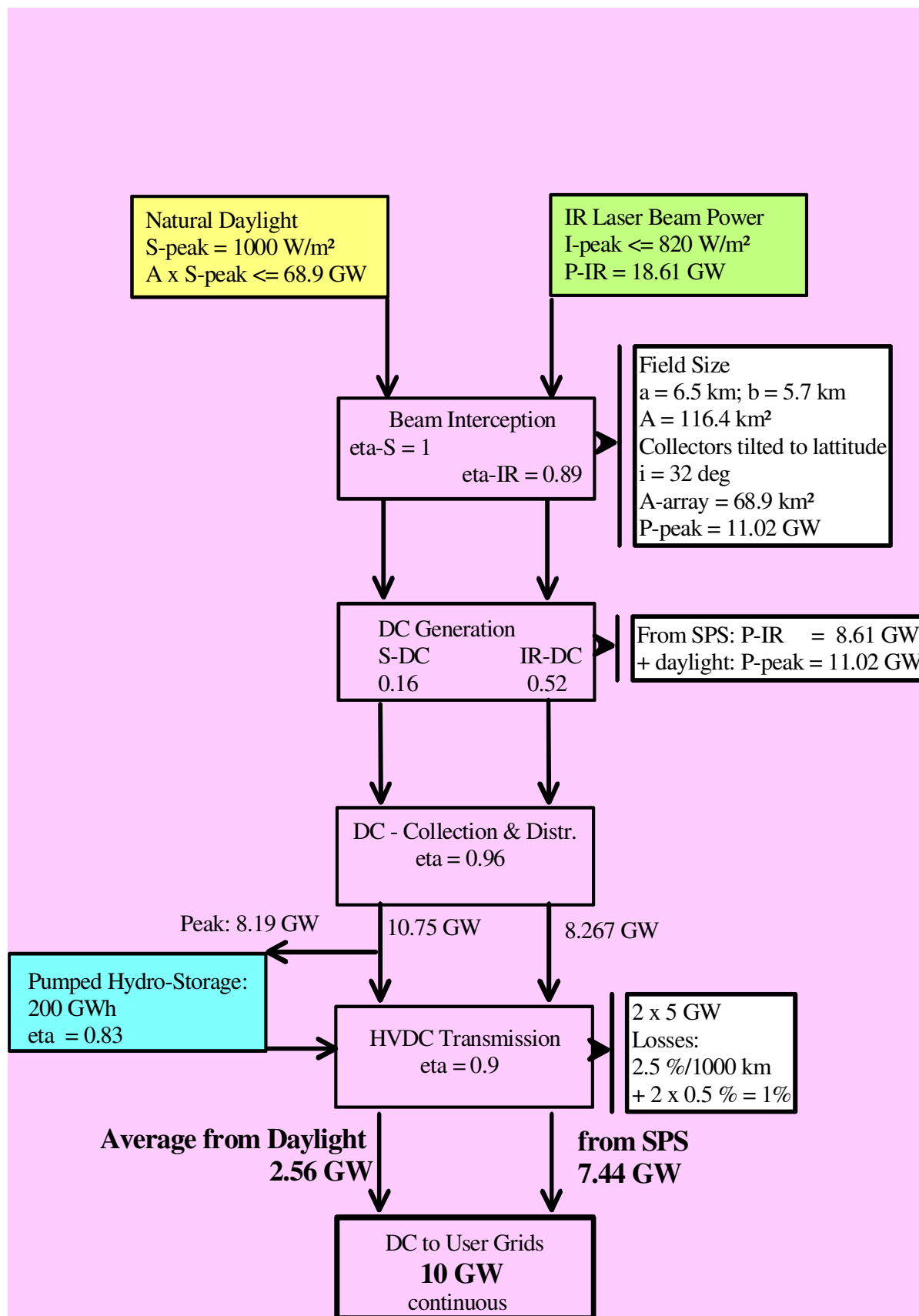


Figure 28. Efficiency and Power Chain for Laser-PV Reception Ground System

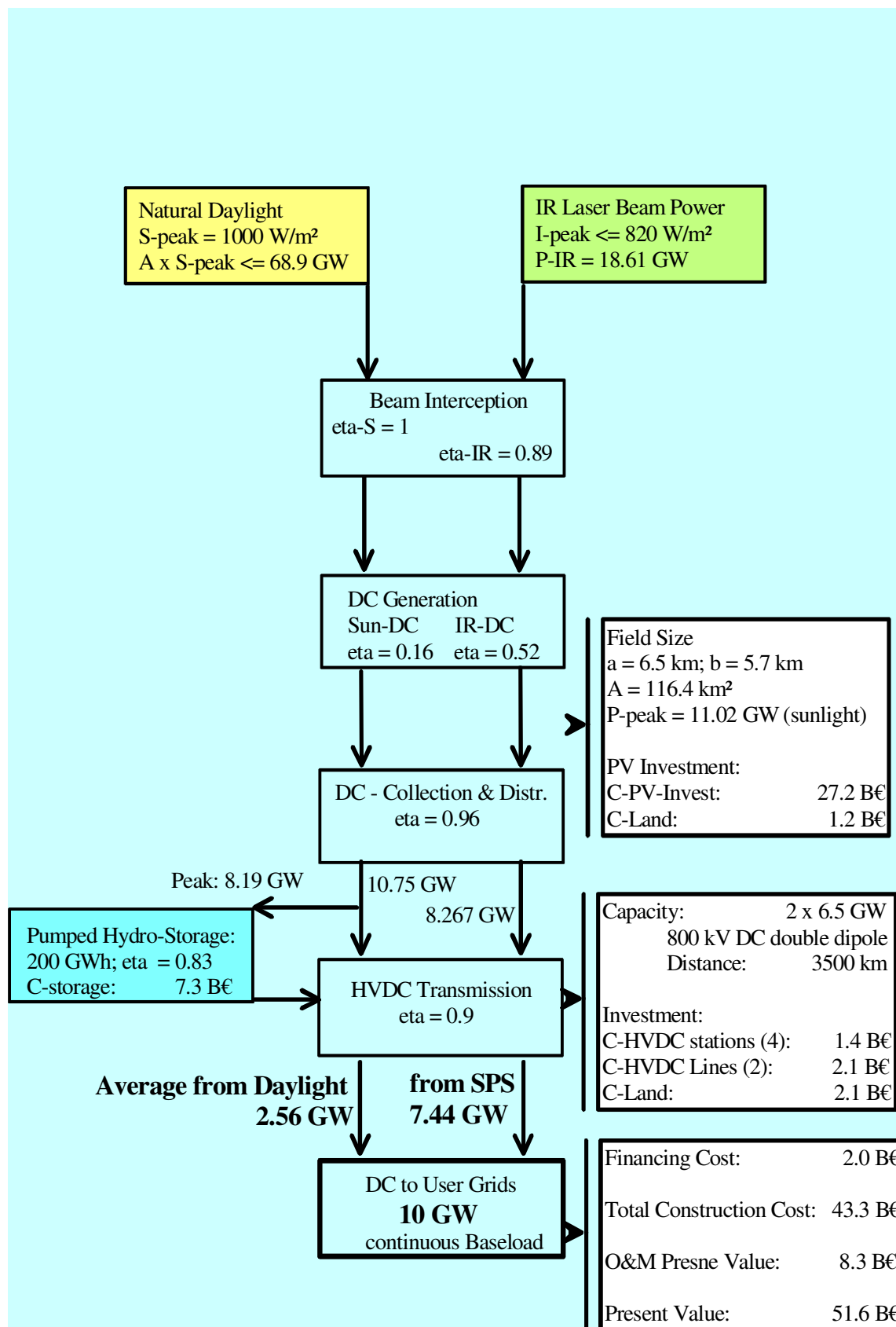


Figure 29. Mass and Cost Data for Laser-PV Ground Reception System



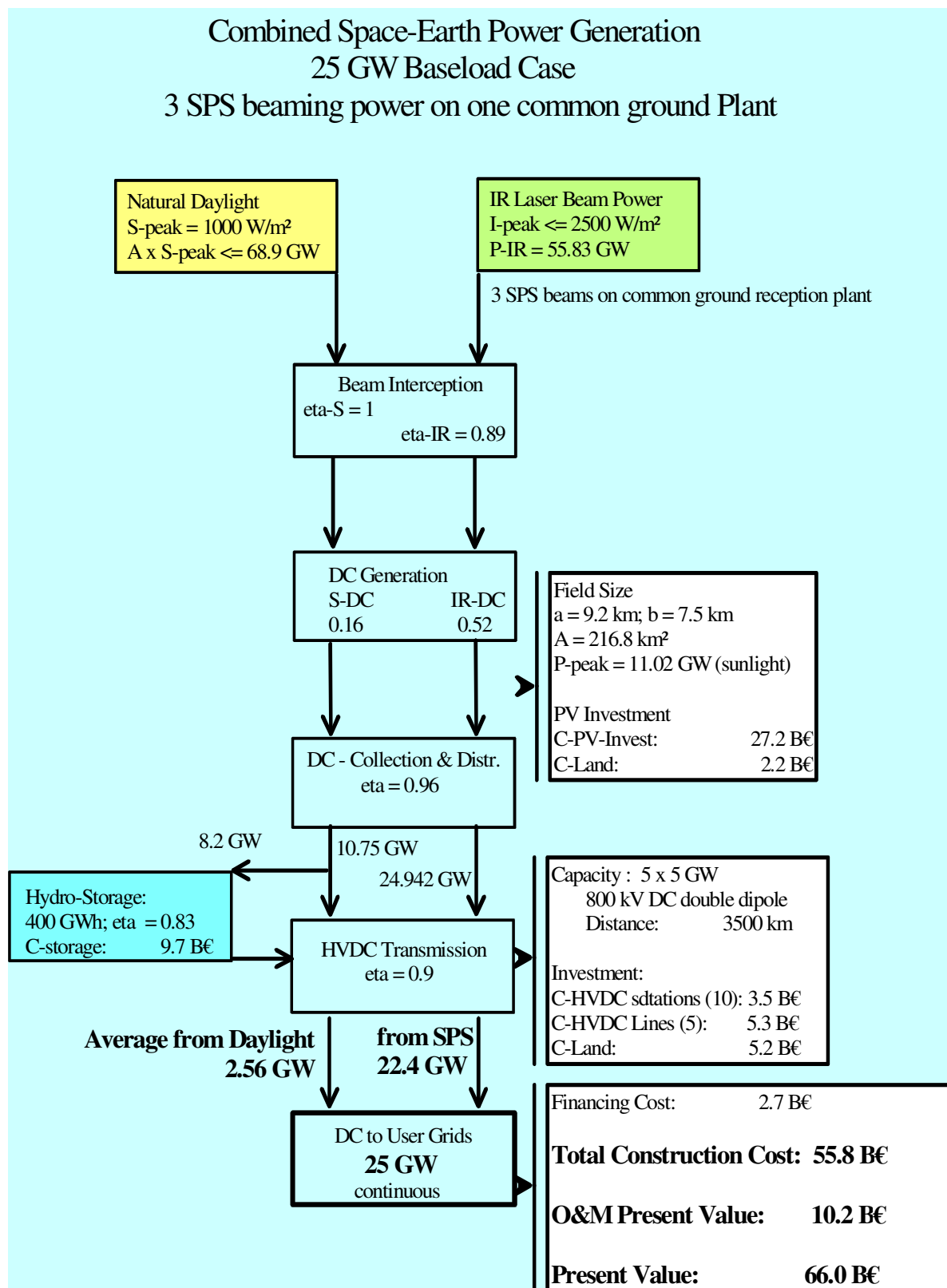


Figure 30. Cost Data for a Combined Sunlight and Laser Radiation Ground Reception System

A cost breakdown for a first operational 10 GW SPS is made. This system generates 7.44 GW supply to the users on ground. Basic assumptions were made for the Earth-to-Orbit (ETO) transportation; the Adler-type Future Launcher System is applied for ETO, and an electric LEO to GEO transfer, with spiralling up the logistics into GEO, taking about two to three weeks trip time:

- o Laser power transmission
- o ADLER Heavy Lift Launch Vehicle (1780 launches per SPS using several launch sites)
- o Electric LEO-to-GEO auto-propulsion
- o 1 year erection time

The cost results are given below. The major contributors to the cost are power generation and transportation:

|                      |                |             |                                                   |
|----------------------|----------------|-------------|---------------------------------------------------|
| Power Generation:    | 37.8 B€        | 42.81%      | ( $\approx$ 5.08 €/W on ground)                   |
| Power Transmission:  | 8.8 B€         | 9.97%       | ( $\approx$ 1.18 €/W on ground)                   |
| Transportation:      | 30.8 B€        | 34.88%      | ( $\approx$ 4.14 €/W on ground)                   |
| Financing:           | 4.2 B€         | 4.75%       | ( $\approx$ 0.56 €/W on ground)                   |
| O & M Present Value: | 6.7 B€         | 7.59%       | ( $\approx$ 0.90 €/W on ground)                   |
| <b>Total:</b>        | <b>88.3 B€</b> | <b>100%</b> | <b>(<math>\approx</math> 11.86 €/W on ground)</b> |

The SPS based on microwave transmission would be by about 30% less expensive, but requires an extra rectenna on ground.

## • Combined Space-Earth PV Systems Base Load Case Evaluation and Synergies

For the sensitivity assessments concerning the evolution of launcher cost, transportation cost and levelised electricity cost (LEC) a usual PC software has been applied. In the following figures the results are depicted.

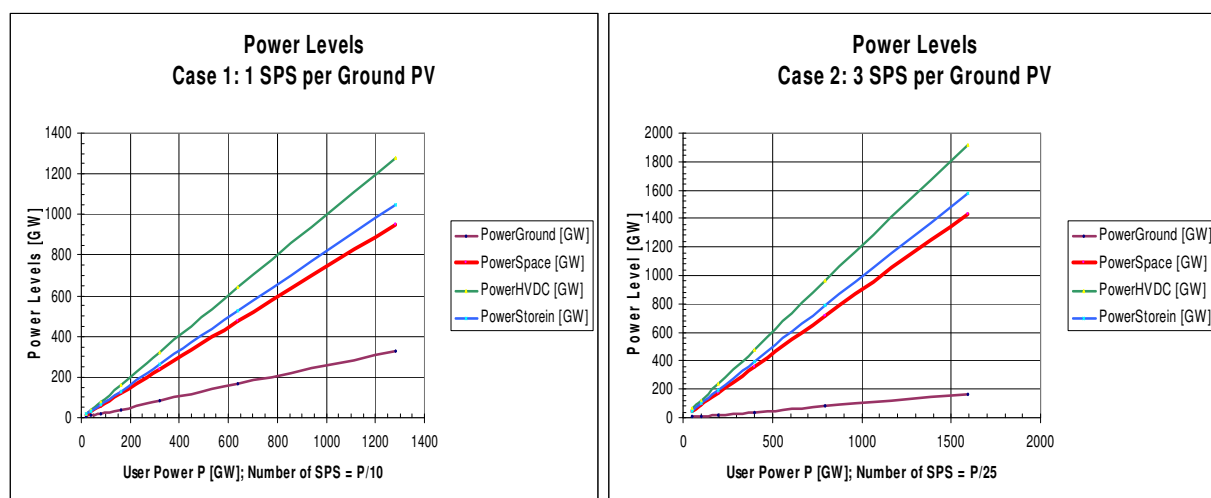


Figure 31. Combined Space-Ground PV System Power Levels for 1 SPS and 3 SPS per PV Ground System and Cost items

The comment on these diagrams is, that the SPS contributes the lion's share to the gained energy, but power ground transmission and storage are also major cost drivers.

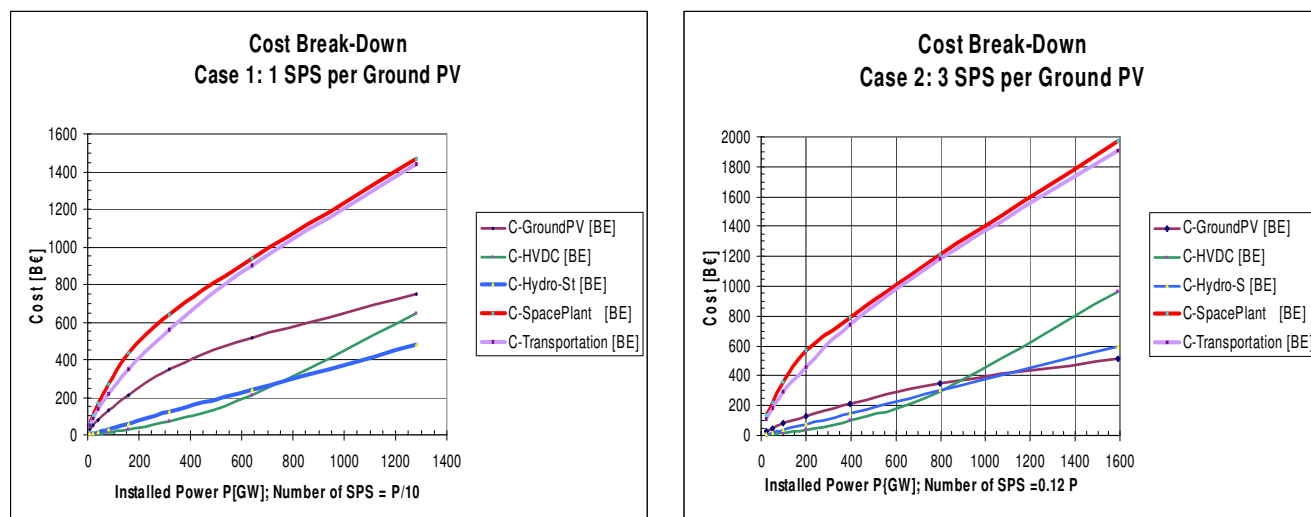


Figure 32. Combined Space-Ground PV System Cost Break Down for 1 SPS and 3 SPS per 1 PV Ground System

The comment on these diagrams is, that the SPS and transportation contribute the lion's share to the total cost, but also PV power ground production is a major cost driver, which specific value may be reduced by increasing the number of SPS in space due to the higher additional laser radiation intensity per area size.

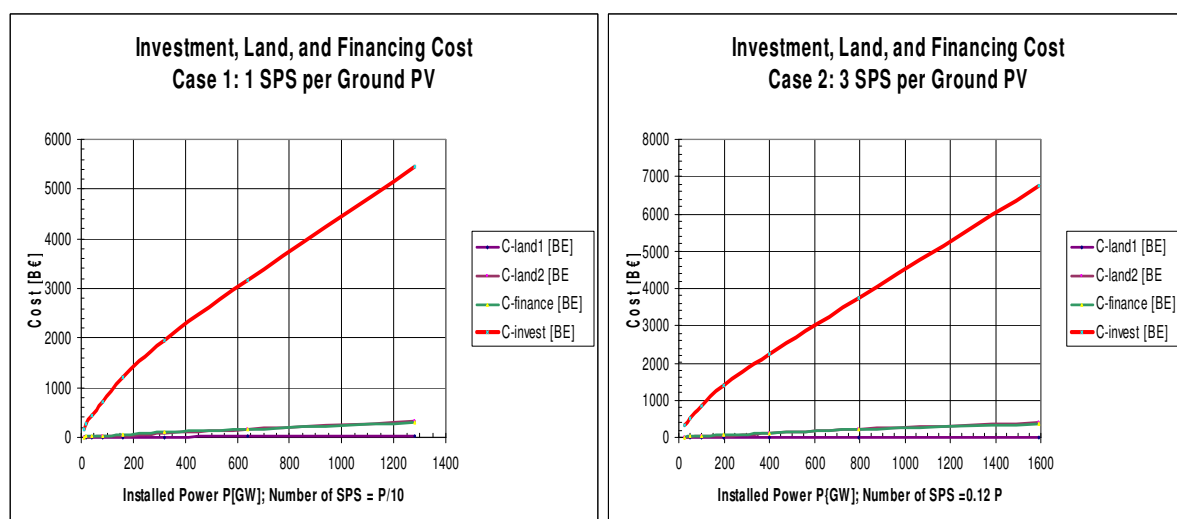


Figure 33. Combined Space-Ground PV System Total Investment Cost for 1 SPS and 3 SPS per 1 PV Ground System

The comment on these diagrams is, that the

- costs are dominated by initial investment in space transportation, SPS, and ground equipment
- costs of land, pre-financing, and operations are of minor importance for the LEC

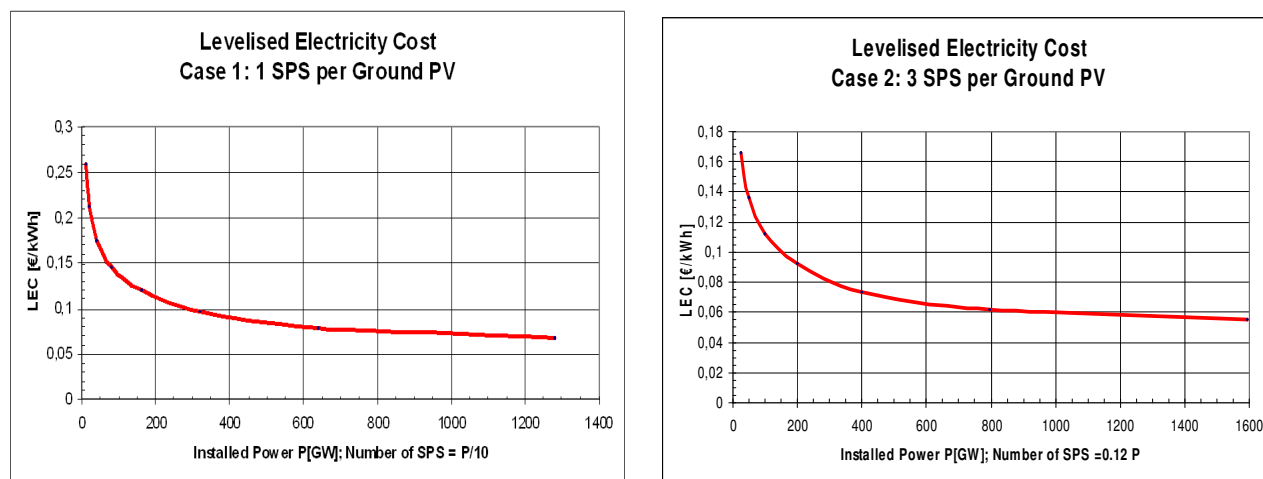


Figure 34. Levelised Electricity Cost for 1 SPS and 3 SPS per PV Ground system

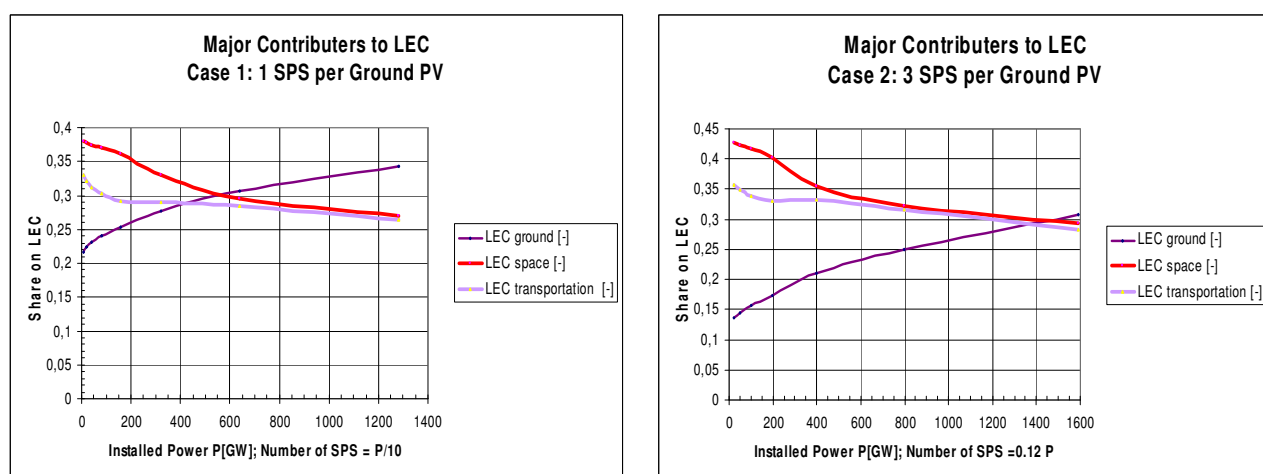


Figure 35. Major Contributors Cost to LEC for 1 SPS and 3 SPS per PV Ground System

Here, Ground includes Ground PV, Hydro storage, and 5500 km HVDC transmission. Here, Ground includes Ground PV, Hydro storage, and 5500 km HVDC transmission. The values of the graphs in Figure 34 and Figure 35 represent an additional EADS internal simulation, based on data provided in this report. However, these results differ somewhat from the ‘official’ results in this report as these latter were done on a fully integrated and consistent way for all power systems, both space-based and terrestrial.

The comment on these diagrams is, that

- the levelised electricity cost, LEC, is in the range of 0.05 to 0.065 €/kWh
- an increase of capacity decreases the LEC due to learning factors
- SPS contributes to 33% to the LEC, and becomes competitive to ground PV at large scale
- space transportation contributes 33% to the LEC

(average specific transportation cost for Earth to GEO between 380 €/kg to 433 €/kg as EADS internal assumption for the simulation here)

The basic conclusions drawn from the sensitivity and model simulations are summarized as follows:

- o Combined Space-Ground PV systems are only competitive to pure Ground PV at large scale, i.e. at a scale above 500 GW:
  - o Specific present value, PV, is in the range of 5,000 to 6,000 €/kW
  - o Levelised electricity cost, LEC, is in the range of 0.05 to 0.065 €/kWh
  - o Almost equal contributions of Transportation, Space Plants, and Ground Segment to LEC
  - o Increasing the number of SPS per Ground PV decreases the LEC slightly
- o Increase of capacity decreases LEC due to learning factors
- o SPS and Space Transportation each contributes about 33% to the LEC
- o Current launch vehicles are only acceptable for initial SPS demonstration.
- o New launch vehicles based on available knowledge and technologies are required,
  - o capable of high frequent launch, (partial) reusability, and series production;
  - o landing of reusable parts / stages at the launch site for rapid turn-around.
- o Cost of land, pre-financing, and operations are of minor importance for LEC.

- **Combined Space-Earth PV - Materials and Energy Consumption per SPS**

For the definition of the material for construction and energy consumption the assumptions were made to consider:

- o Solar Power Plant Reference Design Data
- o Space-Earth Reference System
- o 2020/2030, Configuration: Solar disk in GEO

For the up scaling of the SPS reference system a Linear Scaling Law was applied:

$$1 \text{ SPS} + 1 \text{ Ground PV} = 10 \text{ GW}$$

$$3 \text{ SPS} + 1 \text{ Ground PV} = 25 \text{ GW}$$

$$6 \text{ SPS} + 2 \text{ Ground PV} = 50 \text{ GW}$$

$$9 \text{ SPS} + 3 \text{ Ground PV} = 75 \text{ GW}$$

$$12 \text{ SPS} + 4 \text{ Ground PV} = 100 \text{ GW}$$

In the Table 27 the material and energy efforts are disposed in terms of area and mass in space needed, energy and specific demand. In addition from EADS point of assessment, the energy payback ratio has been calculated. The working assumption was, that the ground PV system similar to that elaborated by DLR is applied, that is in accordance with the principle approach.

The EPT of 56 days presented in the Table 27 is EADS estimate and differ from the EPT values presented in chapter 6 because a different simulation method was applied. The data are contained here, in order to provide a complete picture of the SPS space segment.

It turned out here, that the major contributors to mass and energy requirement for a SPS are the laser system optics and thermal control radiators.

In this table, the data for the complete space segment are contained, its done for single SPS platform with 10 GW performance. It should be noted here, that the launcher structure and propellant and the re-supply is contained as well.

The RAAM, is an re-entry type vehicle of the launcher, to return electronics and avionics equipment. The Solar Cells mentioned are Thin-Film cells, the total mass assumption of the laser system in space is based on future developments and efficiency enhancement of that technology, with the prerequisite of a dedicated laser development for SPS applications. The same basic implication is done here for the launcher system, as this requires a mass production-type of concerning the manufacturing processes and a dedicated launcher development.

Table 27. Construction mass and energy consumption per SPS (10 GW)

|                             | Characterisation                              | Area<br>[km <sup>2</sup> ] | Mass<br>[Mg] | Energy<br>demand<br>[kWh/kg] | Energy<br>demand<br>[GWh] |
|-----------------------------|-----------------------------------------------|----------------------------|--------------|------------------------------|---------------------------|
| <b>Orbital Segment</b>      |                                               |                            |              |                              |                           |
| Module cover glass          | 20 µm float glass foil                        | 110.7                      | 5,756        | 7.5                          | 43.17                     |
| Solar cells (GaAs)          | 5 µm GaAs                                     | 110.7                      | 2,491        | 100.0                        | 249.1                     |
| Collection grids            | 1 µm copper                                   | 8.86                       | 78.85        | 15.6                         | 1.23                      |
| Insulation foils            | 6 µm kapton foil                              | 110.7                      | 730.6        | 12.6                         | 9.2                       |
| Substrate foils             | 8 µm low alloy steel                          | 110.7                      | 7,085        | 15.6                         | 110.53                    |
| Reflector foils             | 6 µm kapton foil                              | 221.4                      | 1,461        | 12.6                         | 18.4                      |
| Reflection layer            | 1 µm aluminium                                | 221.4                      | 598          | 24.5                         | 14.65                     |
| Suspension                  | CFRP tension cables                           |                            | 216          | 7.8                          | 1.69                      |
|                             | Springs: low alloy steel                      |                            | 22           | 15.6                         | 0.34                      |
|                             | Spring casings: CFRP                          |                            | 13           | 15.6                         | 0.20                      |
| Secondary bus bars          | Bare aluminium Al 99.5 cables                 |                            | 4,390        | 24.5                         | 107.56                    |
| Laser system                | GaAs diode stacks & connections               | 1.8 10 <sup>6</sup>        | 1,830        | 100.0                        | 183.0                     |
|                             | Laser optics and fibre optics                 | units                      | 20,670       | 15.0                         | 310.1                     |
| Thermal control radiators   | 44% AL 99.5 + 56% lithium                     | 17.44                      | 29,960       | 24.5                         | 734.0                     |
| Electronics                 |                                               |                            | 1,128        | 40.0                         | 45.12                     |
| Attitude & position control | Low alloy stainless steel                     |                            | 3,490        | 15.6                         | 54.44                     |
| <b>Launch vehicles</b>      |                                               |                            |              |                              |                           |
| Tank shells                 | CFRP (5.4 m tubes with end domes)             | SPS reuse                  | 22,023       | 7.8                          | 17.18                     |
| Payload shrouds             | CFRP (5.4 m tubes with end domes)             | SPS reuse                  | 11,574       | 7.8                          | 90.28                     |
| Cryo-insulation             | PU foam                                       | SPS reuse                  | 2,880        | 9.5                          | 27.36                     |
| Fuel: liquid hydrogen       | LH <sub>2</sub> : electrolysis + Liquifaction |                            | 167,180      | 54.5                         | 9,111                     |
| Oxidiser: liquid oxygen     | LO <sub>2</sub> : electr. + air rect. & liq.  |                            | 1,072,520    | 0.9                          | 965.27                    |
| RAAM (14 modules)           | Aluminium, copper, CFRP                       | 120 flights                | 508.5        | 24.5                         | 12.46                     |
| Resupply (30 years life)    | 0.6% on all items per year                    |                            |              |                              |                           |
| SubTotal (Orb.Segmt.)       |                                               |                            | 79,319       |                              | 12106                     |
| SubTotal (w/o RAAM)         |                                               |                            | 1,355,496    |                              |                           |
| EPT Space                   |                                               |                            | 56 days      |                              |                           |

### 3.4.4 Electricity Demand for Propellant Production

The calculation for the electricity need for the production of transportation fuel is based on the state-of-the-art technology to produce LH<sub>2</sub> and LO<sub>2</sub>. Per SPS (10 GW) the following values are used:

- o LH<sub>2</sub>: 167,180 Mg @ 54.5 kWh/kg = 9.111 E9 kWh (= 32,801 TJ)
- o LO<sub>2</sub>: 1,072,520 Mg @ 0.9 kWh/kg = 9.653 E8 kWh (= 3,475 TJ)

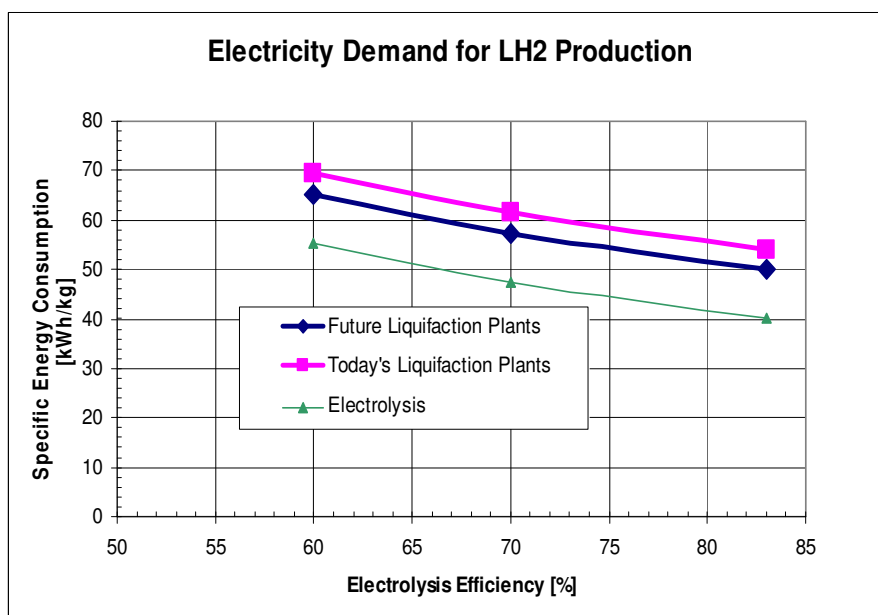


Figure 36. Production of LH<sub>2</sub> rocket fuel is the major energy consumer in SPS construction

So, the conclusion is, that for a capacity of delivering 7.44 GW to users, the SPS recovers the energy spent for space transportation in 56.4 days (1.88 months).

### 3.5 Conclusion

Out of the study investigations the main conclusions could be drawn as follows:

- o The laser transmission technology is given the preference due to its spin-off applications in space and non-space areas, whereas microwave technology was treated in parallel
- o The GEO orbit should be used as preferable operational orbit
- o In the range of higher power levels a scenario with multiple SPS in orbit may become economically attractive in comparison to a pure ground PV system
- o For a sound consolidation a much more detailed study would be needed, both for the laser and the microwave transmission system



## 4 Power Supply by Terrestrial Solar Power Plants

In contrast to the scenarios of power supply from space, which are still in their planning phase, several types of terrestrial power plants exist, delivering energy in various forms for some decades.

Technological data and corresponding costs are therefore well known and can be given with far less uncertainty than for space systems. To get a comprehensive impression of a possible electricity supply by terrestrial solar power plants, several scenarios have been set up for today's state-of-the-art technology as well as also for advanced future technologies as assumed to be available in 2020/2030. To keep comparability to the space system, only solar driven terrestrial power plants have been taken into account, excluding other renewable energies for electricity generation like e.g. wind or hydropower.

On technological side, the terrestrial scenarios are classified in generation of electricity by photovoltaic or Solar Thermal Power Plants at selected sites, daily and/or seasonal storage needs (if necessary) as well as the transmission of power from generation to the supply zone. Necessary capacities and power levels were specified and resulting levelised electricity costs calculated. As obtained prices for base load respectively peak load are different, the cases of a constant 8760 h base load supply and the steadily varying remaining load above base load were treated separately. To reveal possible synergies, further calculations were performed combining SPS and terrestrial systems. Primarily the basic assumptions and definitions of the terrestrial systems for the scenarios will be described.

### 4.1 General Definitions of a Terrestrial Power Supply

The definitions of the scenarios for terrestrial power supply are structured primarily in the general geographic concept of supply and generation zones, in the demand load of the supply zone and its development, the detailed description of the used technologies with its technological specifications and costs, and in a final description of how the calculations have been performed.

#### 4.1.1 Geographical Definition of the Terrestrial Scenario

For the selection and set-up of the generation zones it is important initially to have a look at the spatial distribution of solar irradiation. Solar irradiation must be seen as the "fuel" for the solar power plants showing an over-proportional impact on the pricing.

##### 4.1.1.1 Available Solar Resources

The expectable solar resources for the West and Central Europe supply zone are shown in Table 28 and Table 29. The whole European supply zone is subdivided into 10 zones (see Figure 40) and for each zone annual irradiation sums are listed representatively for 5 selected locations, equally spread over the zone area. Irradiation values comprehend global horizontal, diffuse horizontal as well as direct normal irradiation: GHI, DHI and DNI. In northern European countries like e.g. the British islands, the Scandinavian or the Benelux countries (zones U, N and B) solar irradiation hardly reaches annual sums of 1000 kWh/m<sup>2</sup>a for GHI as well as DNI (DHI is not suitable for electricity generation). Proceeding towards the south irradiation sums are increasing to reach values of 1600 to 1700 kWh/m<sup>2</sup>a as a mean for GHI and up to 2000 kWh/m<sup>2</sup>a for DNI with the exceeding maximum around Seville with 2000 kWh/m<sup>2</sup>a GHI and over 2400 kWh/m<sup>2</sup>a of DNI. The distribution of the annual DNI

irradiation sum, derived from data taken from the Meteosat satellite within the years of 1998 to 2002, is presented in Figure 37 (left side), showing also the increasing solar irradiation towards the south. However, population density is high in Europe and land widely used as can be seen also for Spain on the right hand side picture of Figure 37. Land use is classified by population, industrial or infrastructural use, hydrographic features, protected areas, agriculture and forestry, land with a slope higher than 5° - all of them shown coloured, leaving white only available land. Solar power plants here therefore have to compete with industry and agriculture or forestry, raising the price for solar power plants or also other renewable energies.

Table 28. Reference Cities with Solar Irradiance in Europe (Zones B, D, E, F, G, data [Sat03])

| Zo | Country     | City      | Lat     | Lon     | H   | GHI  | DHI | DNI  |
|----|-------------|-----------|---------|---------|-----|------|-----|------|
| B  | Netherlands | Amsterdam | 52.35°N | 4.92°E  | 0   | 992  | 567 | 848  |
| B  | Netherlands | The Hague | 52.07°N | 4.30°E  | 2   | 1042 | 547 | 952  |
| B  | Belgium     | Brussels  | 50.82°N | 4.32°E  | 62  | 994  | 570 | 833  |
| B  | Belgium     | Liege     | 50.62°N | 5.57°E  | 64  | 990  | 564 | 831  |
| B  | Luxemburg   | Luxemburg | 49.60°N | 6.12°E  | 260 | 1058 | 578 | 898  |
| D  | Germany     | Hamburg   | 53.55°N | 10.00°E | 3   | 938  | 540 | 803  |
| D  | Germany     | Berlin    | 52.52°N | 13.40°E | 35  | 1043 | 541 | 1004 |
| D  | Germany     | Frankfurt | 50.12°N | 8.67°E  | 119 | 1039 | 575 | 871  |
| D  | Germany     | Stuttgart | 48.77°N | 9.17°E  | 253 | 1103 | 559 | 1032 |
| D  | Germany     | Munich    | 48.15°N | 11.57°E | 514 | 1148 | 539 | 1126 |
| E  | Spain       | Barcelona | 41.37°N | 2.17°E  | 31  | 1626 | 554 | 1891 |
| E  | Spain       | Madrid    | 40.40°N | 3.67°W  | 597 | 1755 | 512 | 2137 |
| E  | Spain       | Valencia  | 39.47°N | 0.37°W  | 11  | 1708 | 591 | 1916 |
| E  | Portugal    | Lisbon    | 38.72°N | 9.12°W  | 63  | 1696 | 591 | 1907 |
| E  | Spain       | Sevilla   | 37.37°N | 5.98°W  | 5   | 1955 | 492 | 2486 |
| F  | France      | Paris     | 48.87°N | 2.32°E  | 35  | 1143 | 578 | 1070 |
| F  | France      | Lyon      | 45.75°N | 4.85°E  | 175 | 1313 | 560 | 1378 |
| F  | France      | Bordeaux  | 44.82°N | 0.57°W  | 9   | 1304 | 603 | 1285 |
| F  | France      | Toulouse  | 43.60°N | 1.42°E  | 136 | 1391 | 573 | 1460 |
| F  | France      | Marseille | 43.30°N | 5.40°E  | 54  | 1639 | 488 | 2038 |
| G  | Croatia     | Zegreb    | 45.80°N | 16.00°E | 127 | 1372 | 568 | 1428 |
| G  | Yugoslavia  | Belgrade  | 44.82°N | 20.50°E | 71  | 1553 | 507 | 1868 |
| G  | Macedonia   | Skopje    | 42.00°N | 21.47°E | 247 | 1676 | 531 | 2004 |
| G  | Greece      | Salonica  | 40.62°N | 22.92°E | 0   | 1584 | 615 | 1651 |
| G  | Greece      | Athens    | 37.97°N | 23.72°E | 110 | 1697 | 634 | 1774 |

Zo: Zone, Lat: latitude, Lon: longitude, H height above sea level in m

GHI : annual global horizontal irradiation in kWh/m<sup>2</sup>a

DHI : annual diffuse horizontal irradiation in kWh/m<sup>2</sup>a

DNI : annual direct normal irradiation in kWh/m<sup>2</sup>a

Table 29. Reference Cities with Solar Irradiance in Europe (Zones, I, N, P, S, U, data [Sat03])

| Zo | Country        | City       | Lat     | Lon     | H   | GHI  | DHI | DNI  |
|----|----------------|------------|---------|---------|-----|------|-----|------|
| I  | Italy          | Milan      | 45.47°N | 9.20°E  | 122 | 1329 | 561 | 1370 |
| I  | Italy          | Rome       | 41.90°N | 12.47°E | 19  | 1572 | 565 | 1752 |
| I  | Italy          | Bari       | 41.12°N | 16.85°E | 3   | 1742 | 501 | 2122 |
| I  | Italy          | Naples     | 40.82°N | 14.25°E | 9   | 1662 | 550 | 1918 |
| I  | Italy          | Palermo    | 38.12°N | 13.37°E | 4   | 1715 | 583 | 1873 |
| N  | Finland        | Helsinki   | 60.17°N | 24.29°E | 11  | 1028 | 465 | 1193 |
| N  | Norway         | Oslo       | 59.92°N | 10.75°E | 19  | 879  | 479 | 870  |
| N  | Sweden         | Stockholm  | 59.32°N | 18.05°E | 16  | 974  | 487 | 1079 |
| N  | Sweden         | Göteborg   | 57.72°N | 11.97°E | 2   | 1010 | 475 | 1161 |
| N  | Denmark        | Copenhagen | 55.67°N | 12.57°E | 0   | 1022 | 504 | 1091 |
| P  | Poland         | Poznan     | 52.42°N | 16.97°E | 50  | 1051 | 544 | 984  |
| P  | Poland         | Warsaw     | 52.25°N | 21.00°E | 94  | 1084 | 551 | 1032 |
| P  | Czech Republic | Prague     | 50.07°N | 14.47°E | 245 | 1123 | 565 | 1065 |
| P  | Slovakia       | Bratislava | 48.15°N | 17.12°E | 137 | 1251 | 558 | 1247 |
| P  | Hungary        | Budapest   | 47.50°N | 19.07°E | 97  | 1331 | 568 | 1367 |
| S  | Austria        | Vienna     | 48.20°N | 16.37°E | 171 | 1204 | 577 | 1133 |
| S  | Austria        | Innsbruck  | 47.27°N | 11.40°E | 562 | 1238 | 567 | 1296 |
| S  | Switzerland    | Bern       | 46.92°N | 7.47°E  | 536 | 1250 | 528 | 1311 |
| S  | Switzerland    | Geneva     | 46.20°N | 6.17°E  | 376 | 1285 | 542 | 1311 |
| S  | Slovenia       | Ljubljana  | 46.05°N | 14.50°E | 298 | 1287 | 563 | 1273 |
| U  | Ireland        | Dublin     | 53.32°N | 6.25°W  | 9   | 977  | 584 | 831  |
| U  | United Kingdom | Glasgow    | 55.82°N | 4.25°W  | 66  | 908  | 558 | 761  |
| U  | United Kingdom | Manchester | 53.50°N | 2.22°W  | 70  | 894  | 563 | 671  |
| U  | United Kingdom | Birmingham | 52.47°N | 1.92°W  | 140 | 930  | 574 | 738  |
| U  | United Kingdom | London     | 51.50°N | 0.12°W  | 15  | 938  | 578 | 739  |

LEGEND: SEE TABLE 28.

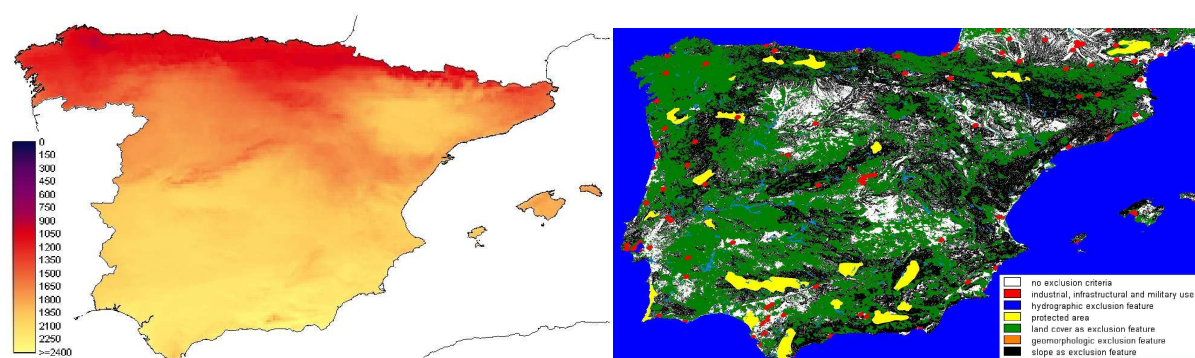


Figure 37. Left side: Direct Normal Irradiation (DNI) of Spain, derived from METEOSAT Satellite images as an average of the years 1998-2002; right side: exclusion criteria for land use in Spain and Portugal

Proceeding further to the south, to the so-called Sunbelt within the African continent, the irradiation is further increasing significantly. Figure 38 shows annual direct normal irradiance sums of nearly up to

3000 kWh/m<sup>2</sup>a in the middle and east regions of the Sahara desert. Table 30 lists detailed annual irradiation sums for several cities of North African countries: GHI ranges from values of 2000 kWh/m<sup>2</sup>a in Morocco to 2400 kWh/m<sup>2</sup>a in Egypt and DNI from 2300 to 3000 kWh/m<sup>2</sup>.

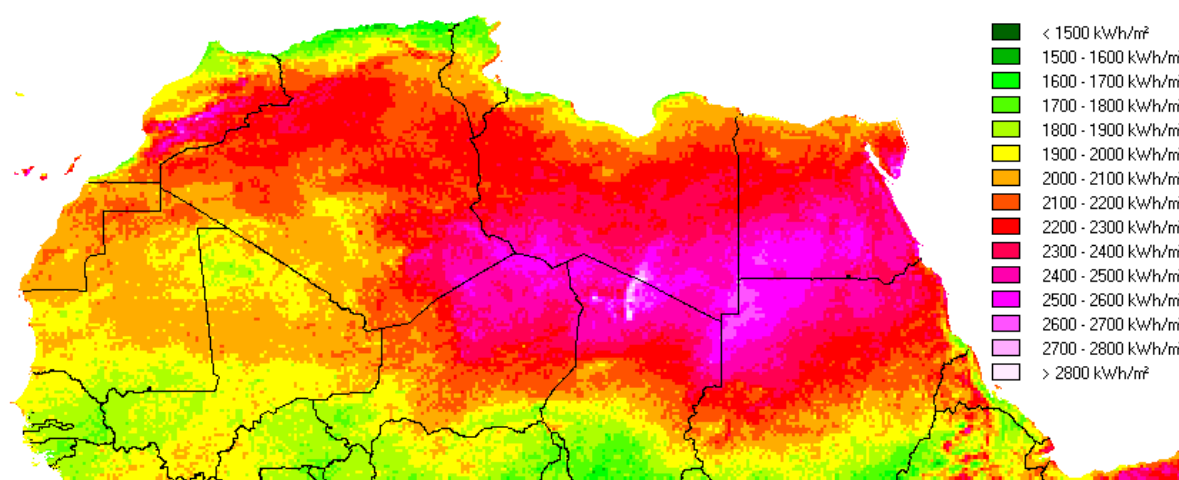


Figure 38. Map of the annual Direct Normal Irradiation (DNI) sum of northern Africa

Table 30. Reference Cities with Solar Irradiance in North Africa (Zones A1, A2, A3)

| Zo  | Country    | City      | DS | Lat     | Lon     | H    | GHI  | DHI | DNI  |
|-----|------------|-----------|----|---------|---------|------|------|-----|------|
| A1  | Morocco    | Jerada    | S  | 34.30°N | 2.15°W  | 1097 | 2095 | 502 | 2643 |
| A1a | Morocco    | Kenitra   | S  | 34.37°N | 6.60°W  | 24   | 2009 | 540 | 2338 |
| A1  | Morocco    | Ourzazate | M  | 30.93°N | 6.90°W  | 1140 | 2117 | 605 | 2446 |
| A1  | Algeria    | Saida     | S  | 34.82°N | 0.15°E  | 818  | 2018 | 504 | 2502 |
| A1  | Algeria    | Bechar    | M  | 31.62°N | 2.33°W  | 772  | 2107 | 610 | 2431 |
| A1b | Mauritania | Atar      | M  | 20.48°N | 13.05°E | 225  | 2189 | 747 | 2150 |
| A2  | Algeria    | Djelfa    | S  | 34.67°N | 3.25°E  | 1138 | 2079 | 491 | 2624 |
| A2  | Algeria    | In Amenas | M  | 28.05°N | 9.63°E  | 561  | 2195 | 613 | 2520 |
| A2  | Tunisia    | Qafsah    | S  | 34.42°N | 8.77°E  | 312  | 1984 | 554 | 2321 |
| A2  | Libya      | Sehba     | M  | 27.02°N | 14.43°E | 432  | 2163 | 659 | 2338 |
| A2  | Libya      | Kufra     | M  | 24.22°N | 23.30°E | 435  | 2470 | 458 | 3046 |
| A3  | Egypt      | Sohag     | M  | 26.57°N | 31.70°E | 61   | 2326 | 502 | 2733 |
| A3  | Egypt      | Luxor     | M  | 25.67°N | 32.70°E | 82   | 2395 | 431 | 2949 |
| A3  | Egypt      | Dakhla    | M  | 25.48°N | 29.00°E | 106  | 2439 | 421 | 3038 |
| A3  | Egypt      | El Kharga | M  | 25.45°N | 30.53°E | 533  | 2426 | 414 | 3014 |
| A3  | Egypt      | Aswan     | M  | 23.97°N | 32.78°E | 192  | 2466 | 405 | 3071 |

Zo: Zone, Lat: latitude, Lon: longitude, H height above sea level in m; DS : data source: M:[Met03], S:[Sat03]

GHI, DHI, DNI: annual global horizontal, diffuse horizontal and direct normal irradiation in kWh/m<sup>2</sup>

Taking into account land use in North Africa, land there is widely available as huge areas are unused in the Sahara desert (Figure 39). As further exclusion feature geomorphologic structures like dunes with a sufficient safety margin have to be considered. As the calculations within this study will demonstrate, only a small portion of the available land area will be necessary to cover the whole electricity demand of Europe. Transmission losses while transporting the electricity to Europe are far

lower than the additional gains by changing over to North Africa. Thus, North Africa shows outstanding advantages for the installation of solar power plants.

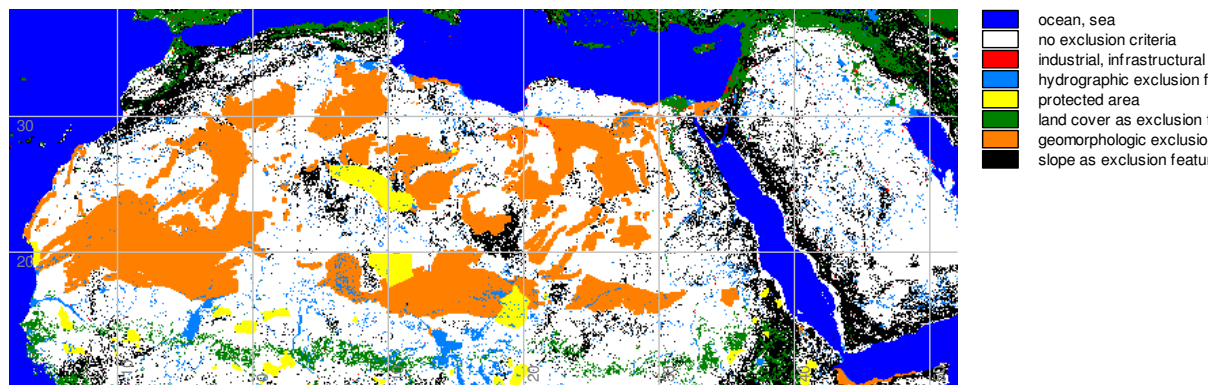


Figure 39. Map of northern Africa with exclusion features for installation of solar thermal power plants

#### 4.1.1.2 Definition of Supply and Generation Zones

Bearing in mind the small amount of available land in Europe and significantly higher irradiation values in North Africa, it is economically reasonable at least for scenarios of full power supply of Europe to place the generation of electricity over to the northern African countries. Figure 40 shows the proposed constellation of supply and generation zones.

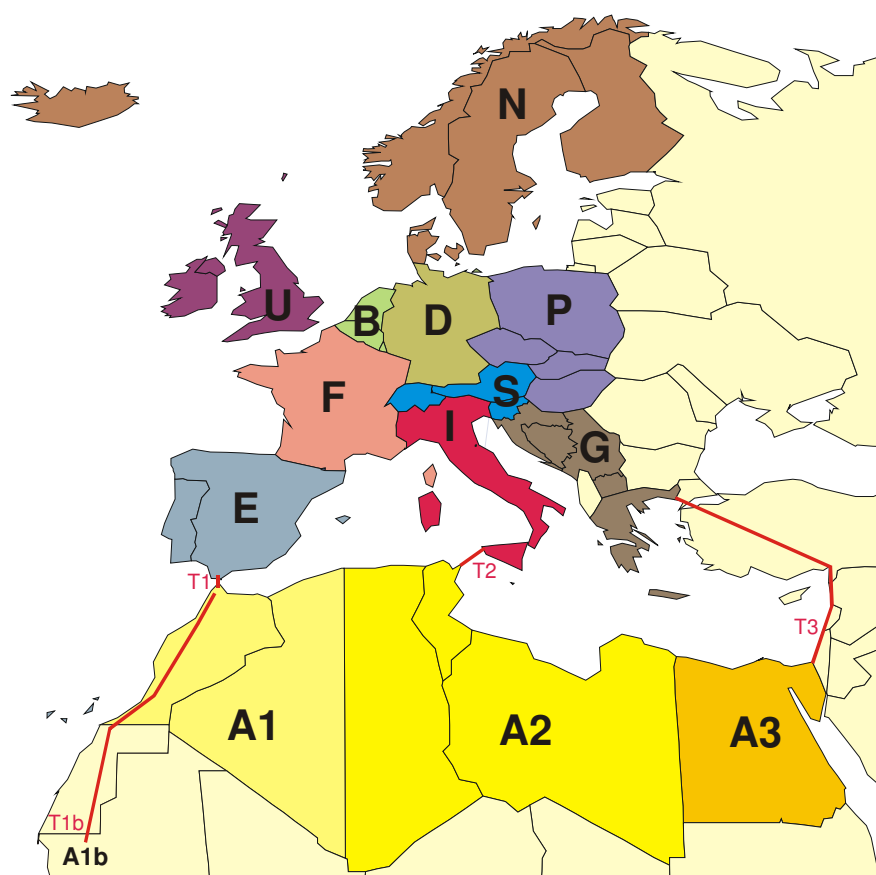


Figure 40 Definition of Supply and Generation Regions in Europe and North Africa

The supply zone of West and Central Europe is cut in 10 zones, named B to U containing the countries as listed in Table 31, accounting for structural and/or geographic features. The generation zone is located in North Africa, separated in 3 zones as stated in

Table 32. The separation in these 3 zones is due to three favourable possibilities of connecting the African continent to Europe via transmission lines T1 to T3. They are assumed to be HV DC lines as T1 connecting Morocco to Spain yet exists by now. Among the different zones of the supply zone it is assumed that electricity will be exchanged and transported also by HV DC lines while distributed within each zone by the conventional AC net.

Locating the whole generation to North Africa may seem unrealistic at first glance. Nevertheless, the calculations have been performed like this for two reasons: firstly to make the calculations more comparable to the space scenario where the ground receiver also is located to unpopulated and – with higher probability – cloudless regions in the African sunbelt; secondly, accounting only on solar energy, it is not realistic that the whole electricity supply for Europe will totally rely on solar power generation within Europe itself. However, in reality this approach is not necessary because in reality there will be a mixture of different types of renewables available. As yet mentioned, other types of renewables, besides solar energy, will not be regarded within this study to make the space and terrestrial solutions comparable. Currently several projects for installation of solar thermal power plants are under way in southern European countries as well as there is an increasing interest in projects in several northern African countries.

Table 31. Supply and Generation Regions in Europe

| Zone Z | Countries                                                  |
|--------|------------------------------------------------------------|
| B      | Belgium, Netherlands, Luxembourg                           |
| D      | Germany                                                    |
| E      | Spain, Portugal                                            |
| F      | France                                                     |
| G      | Greece, Federal Republic of Yugoslavia, Macedonia, Croatia |
| I      | Italy                                                      |
| N      | Denmark, Norway, Sweden, Finland (Iceland)                 |
| P      | Poland, Czech Republic, Slovak Republic, Hungary           |
| S      | Switzerland, Austria, Slovenia                             |
| U      | United Kingdom, Ireland                                    |

Table 32. Generation Regions in North Africa

| Zone Z | Countries                                          |
|--------|----------------------------------------------------|
| A1     | North Africa West (Morocco, West Algeria)          |
| A1b    | Mauritania                                         |
| A2     | North Africa Center (East Algeria, Tunisia, Libya) |
| A3     | North Africa East (Egypt)                          |

### 4.1.2 Definition of the European Electricity Demand

Before setting up scenarios and starting calculations, it is important to identify and analyze the electricity demand within the supply zone. This has been done in detail for the load curves of the year 2000 and in general also for the consumption of the decades before to get an impression on how the demand may develop in the future. For comprehension purposes it is furthermore important to have defined and be able to distinguish the terms “base load” and (instead of “peak load”) “remaining load”.

#### 4.1.2.1 Today Demand Load Curves

Real load curves have been available for the electricity grids of UCTE and CENTREL, enclosing the zones B,D,E,F,G,I, P and S [UCTE00]. Load curves were given for the 3<sup>rd</sup> Wednesday (representative for each of the workdays), the 3<sup>rd</sup> Saturday and the 3<sup>rd</sup> Sunday of each month of the year 2000 (see Figure 41 and Figure 42). To get a load curve with hourly resolution needed for detailed simulation runs, the time in between was simply interpolated. Thereby extreme days with exceeding high loads as e.g. an extraordinary cold winter day are not considered. However, this has no influence on the outcome as it results only in scaling the amount of the power levels, which are to be calculated. Furthermore, the real load curve is no constant but varying from one year to another.



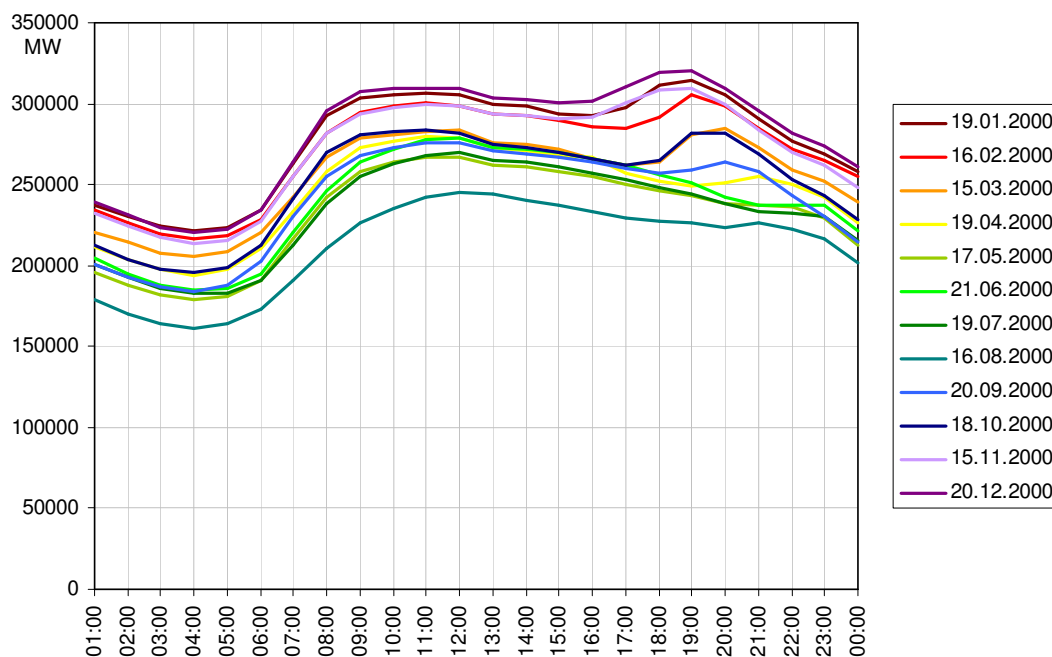


Figure 41 Hourly Load Values of UCTE and CENTREL (Zones B,D,E,F,G,I, P and S) on the 3<sup>rd</sup> Wednesday of all months in the year 2000 (Data: [UCTE00] and own calculations)

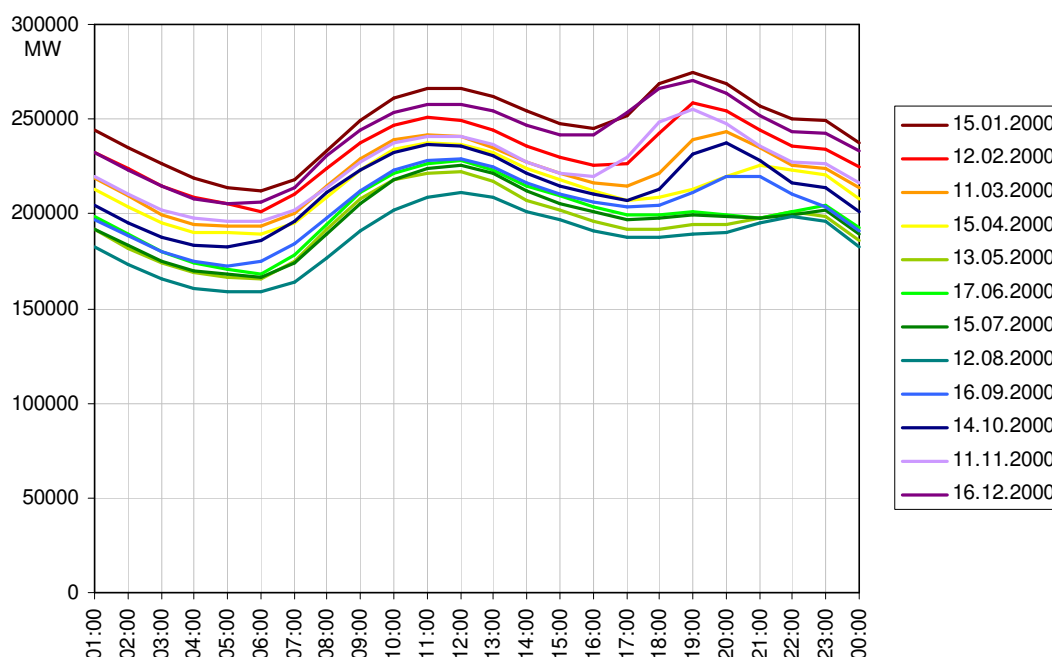


Figure 42. Hourly Load Values of UCTE and CENTREL (Zones B,D,E,F,G,I, P and S) on the 3<sup>rd</sup> Saturday of all months in the year 2000 (Data: [UCTE00] and own calculations)

#### 4.1.2.2 Definition of base and remaining load

Real peak load power plants achieve only 2,000 or less operating hours during a year. They are usually used for covering power peaks, which could only difficultly be covered by base and intermediate load



power plants. Typical peak load power plants are gas turbines or pumped storage hydro power plants today. In general, it is also possible to use solar power plants to cover this peak load. However, it is very difficult to estimate the development in peak load for over the next decades since change in supply structures will also change peak load characteristics significantly.

For this study it was assumed to consider middle and peak load as “peak load”. This is the remaining load when subtracting the base load from the load curve. Base load is defined as the minimal value of the load curve, occurring once within the year. This means the maximal constant power, which is necessary throughout all 8,760 hours of the year. This definition is necessary to achieve possible synergies with space-based systems covering mainly base load. Figure 43 shows the cumulated amount of hours during which the corresponding power was necessary in the determined load curve. The whole annual electricity consumption in 2000 within each zone, its corresponding population and the grid operator are listed in Table 33. Additionally, yet installed hydroelectricity in each zone has been taken into account, as it will continue running anyhow.

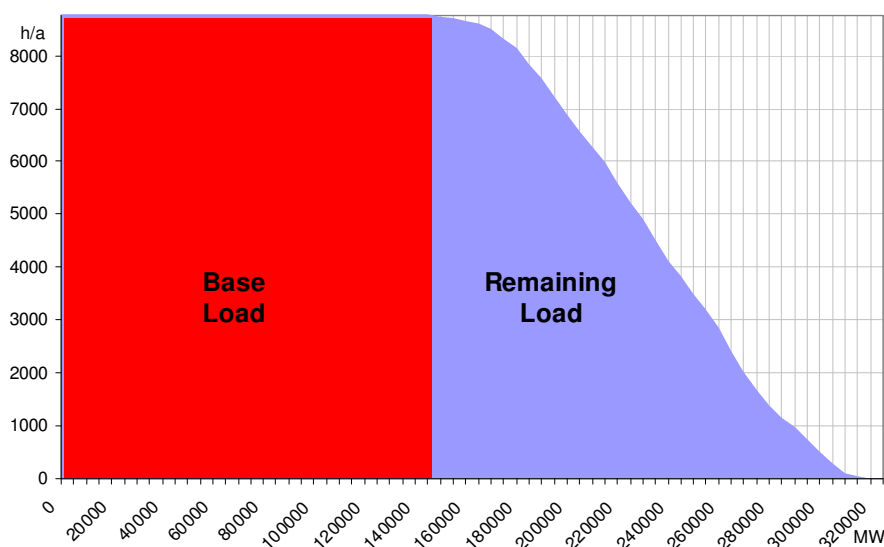


Figure 43. Full load hours over the power for the demand of UCTE and CENTREL (Zones B,D,E,F,G,I, P and S) in the year 2000 (Data: [UCTE00] and own calculations)

Table 33. Supply Data of Supply Zones in Europe for the Reference Year 2000  
(sources: [UCT00, NOR00, IEA02, DOE03])

| Zone Z       | Inhabitants<br>in millions | Transmission<br>system | Consumption<br>in TWh/a | Hydroelectricity<br>in TWh/a |
|--------------|----------------------------|------------------------|-------------------------|------------------------------|
| B            | 26.6                       | UCTE                   | 160.5                   | 2.6                          |
| D            | 82.2                       | UCTE                   | 494.0                   | 23.6                         |
| E            | 49.9                       | UCTE                   | 233.0                   | 43.0                         |
| F            | 60.4                       | UCTE                   | 427.5                   | 67.6                         |
| G            | 21.0                       | UCTE                   | 101.9                   | 23.0                         |
| I            | 57.7                       | UCTE                   | 297.7                   | 50.3                         |
| N            | 24.1                       | NORDEL                 | 392.1                   | 240.7                        |
| P            | 64.4                       | CENTREL                | 254.3                   | 11.5                         |
| S            | 17.3                       | UCTE                   | 118.3                   | 83.5                         |
| U            | 63.6                       | UKTSOA/TSOI            | 362.3                   | 5.9                          |
| <b>Total</b> | <b>467.1</b>               |                        | <b>2,841.6</b>          | <b>551.7</b>                 |

Table 34 shows the average and base load of all supply zones as well as their installed hydroelectric power. The total average load is 324 GW and base load 196 GW. Considering the 42 GW hydroelectric power, which are generated there and have to be subtracted from the existing load, about 150 GW remain as full supply for West and Central Europe. This value does not represent the real base load amount but only a rough estimation, because in reality the minimum levels of the different zones will not all occur at the same time. Finally, base load power supply by terrestrial power plants for today's state-of-the-art scenario has been calculated for power levels of 0.5 GW, 5 GW, 10 GW, 100 GW and 150 GW as full supply.

Table 34. Base Load Data of Supply Zones in Europe for the Reference Year 2000  
(sources: [UCT00], own assumptions)

| Zone         | Average Load    | Base Load<br>(8,760 h/a)      | Hydro Power <sup>e)</sup> | Remaining Base Load            |
|--------------|-----------------|-------------------------------|---------------------------|--------------------------------|
| B            | 18.3 GW         | 11.0 GW                       | 0.1 GW                    | 10.9 GW                        |
| D            | 56.4 GW         | 28.3 GW                       | 1.5 GW                    | 26.8 GW                        |
| E            | 26.6 GW         | 17.2 GW                       | 3.1 GW                    | 14.1 GW                        |
| F            | 48.8 GW         | 29.5 GW                       | 5.0 GW                    | 24.5 GW                        |
| G            | 11.6 GW         | 6.7 GW                        | 1.8 GW                    | 4.9 GW                         |
| I            | 34.0 GW         | 20.2 GW                       | 3.5 GW                    | 16.7 GW                        |
| N            | 44.8 GW         | <sup>e)</sup> 20.0 GW         | 19.2 GW                   | 0.8 GW                         |
| P            | 29.0 GW         | 19.3 GW                       | 0.7 GW                    | 18.6 GW                        |
| S            | 13.5 GW         | 7.4 GW                        | 6.4 GW                    | 1.0 GW                         |
| U            | 41.4 GW         | <sup>e)</sup> 26.0 GW         | 0.5 GW                    | 25.5 GW                        |
| <b>Total</b> | <b>324.3 GW</b> | <sup>b)</sup> <b>195.7 GW</b> | <b>41.8 GW</b>            | <sup>b)</sup> <b>~150.0 GW</b> |

b) minimum base load levels can not be added because they do not all occur at the same time.

e) own estimations, assuming: hydroelectric base load =  $0.7 \cdot (\text{generation} - 0.75 \cdot \text{consumption of pumps}) / 8760\text{h}$ .

### 4.1.2.3 Assumptions for Development of Demand load in 2020/2030

To estimate how the power demand may develop in the future, a look to the recent decades is necessary. Table 35 shows growth rates of electricity demand for Germany, France and Italy since 1980 and for the other countries of the supply zone since 1992. The average growth rate was 2%. As the countries signed the Kyoto protocol promising to reduce CO<sub>2</sub> emissions, slightly reduced growth rates have been assumed for the future, averaging in 1.5% until the years of 2020/2030.

Table 35. Annual growth rates for the Electricity Demand (sources: [DOE03; DOE03b])

| Zone           | 1980-2000 | 1992-2001    | Assumed Growth Rates for 2020/2030 |
|----------------|-----------|--------------|------------------------------------|
| B              | NA        | 2.8 %        | 1.5 %                              |
| D              | 0.7 %     | 1.0 %        | 1.0 %                              |
| E              | NA        | 4.7 %        | 2.5 %                              |
| F              | 3.7 %     | 1.8 %        | 1.5 %                              |
| G              | NA        | 2.3 %        | 2.5 %                              |
| I              | 1.9 %     | 2.4 %        | 2.0 %                              |
| N              | NA        | 1.4 %        | 1.0 %                              |
| P              | NA        | 1.4 %        | 2.0 %                              |
| S              | NA        | 1.9 %        | 1.5 %                              |
| U              | NA        | 2.0 %        | 1.0 %                              |
| <b>Average</b> | <b>NA</b> | <b>2.0 %</b> | <b>1.5 %</b>                       |

Starting from the today consumption of total 2,844 TWh/a and assuming the presented growth rates, the annual consumptions for the years 2020 and 2030 as listed in Table 36 will be expected. Compared to 2000 this means an increase of 35% until 2020 and of nearly 60% until the year 2030. The corresponding minimal, average and maximal power demand loads are presented in Table 37.

For estimations about the whole supply zone B-U the known data for the UCTE grid were multiplied by a factor of 136.1%, representing the augmentation when extending the consumption within the UCTE grid to the whole supply zone B-U. Demand loads for the whole supply zone are also shown for the years 2020 and 2030, showing an increase of the minimum load (base load) from about 200 GW (without respecting hydroelectricity) to more than 300 GW. Remaining load ranges from 240 GW in 2000 to 380 GW in 2030, also without taking into account hydroelectricity.

Table 36. Development of Annual Consumption with assumed Annual Growth Rates

| Zone         | Consumption 2000<br>in TWh/a | Consumption 2020<br>in TWh/a | Consumption 2030<br>in TWh/a |
|--------------|------------------------------|------------------------------|------------------------------|
| B            | 160.5                        | 216.2                        | 250.9                        |
| D            | 494.0                        | 602.8                        | 665.8                        |
| E            | 233.0                        | 381.8                        | 488.7                        |
| F            | 427.5                        | 575.8                        | 668.2                        |
| G            | 101.9                        | 167.0                        | 213.7                        |
| I            | 297.7                        | 442.4                        | 539.2                        |
| N            | 392.1                        | 478.4                        | 528.5                        |
| P            | 254.3                        | 377.9                        | 480.6                        |
| S            | 118.3                        | 159.3                        | 184.9                        |
| U            | 362.3                        | 442.1                        | 488.3                        |
| <b>Total</b> | <b>2,841.6</b>               | <b>3,843.6</b>               | <b>4,489.0</b>               |

Table 37. Development of Demand Loads based on UCTE Load Curves of the Year 2000 with assumed Annual Growth Rates and Scaling UCTE Load by 136.1% to Zones B-U

|              | UCTE<br>Year 2000<br>in GW | Zone B-U<br>Year 2000<br>in GW | Zone B-U<br>Year 2020<br>in GW | Zone B-U<br>Year 2030<br>in GW |
|--------------|----------------------------|--------------------------------|--------------------------------|--------------------------------|
| Minimum load | 143.75                     | 195.7                          | 264.7                          | 309.2                          |
| Average load | 238.24                     | 324.3                          | 438.7                          | 512.3                          |
| Maximum load | 320.16                     | 435.8                          | 589.5                          | 688.5                          |

However, although the assumptions seem reasonable, it is doubtful that the future demand represents a realistic number to be covered by solar energy. For a more realistic estimation also the development and power deliverance of other renewables has to be taken into account. This was done exemplarily for wind power, which in 2003 reached a contribution of 3.1% to the German gross electricity consumption, showing high growth rates in the recent years: Table 38 shows the cumulated wind power installations within most of the countries in Europe from 1995 to 2002. As can be noted, total installation raised from 2.5 GW in 1995 to 23.2 GW in 2002 with growth rates between 32 and 46%. Besides hydroelectric power with a contribution of 3.5% to the gross electricity consumption (in Germany), huge potentials remain for the set-up of wind power in Europe. The contribution of further renewables lies below 1%.

The future development of wind power is not known exactly as it depends strongly on the political will and legislation but is assumed to grow steadily although with a somewhat decreasing growth rate. The outcome of scenarios with a development of wind power with growth rates of only 10, 15 and 20% until the year 2030 is presented in Table 39. The installed capacity will result in an amount between 335 GW and 3.8 TW, reaching the value of maximum load with a growth rate somewhere between 10 and 15%. For covering the total power demand of the year 2030, a growth rate between 15 and 20% will be sufficient. However, this numbers only tell integrated annual respectively maximal

numbers, so an hourly evaluation has to be done to account for temporally differing supply and demand.

Table 38. Cumulated Wind Power Installations in Europe

| MW             | 1995         | 1996          | 1997          | 1998          | 1999          | 2000          | 2001          | 2002          |
|----------------|--------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Germany        | 1,132        | 1,545         | 2,080         | 2,874         | 4,443         | 6,113         | 8,754         | 12,001        |
| Spain          | 133          | 249           | 512           | 834           | 1,225         | 2,538         | 3,337         | 4,830         |
| Denmark        | 637          | 857           | 1,116         | 1,450         | 1,761         | 2,364         | 2,534         | 2,880         |
| Netherlands    | 249          | 299           | 325           | 363           | 411           | 449           | 483           | 686           |
| Italy          | 33           | 71            | 100           | 180           | 283           | 427           | 697           | 785           |
| UK             | 200          | 270           | 320           | 334           | 353           | 406           | 474           | 552           |
| Sweden         | 69           | 105           | 117           | 150           | 215           | 241           | 290           | 328           |
| Greece         | 28           | 29            | 29            | 39            | 82            | 226           | 299           | 276           |
| Ireland        | 7            | 11            | 51            | 63            | 73            | 129           | 153           | 137           |
| Portugal       | 9            | 20            | 38            | 60            | 60            | 99            | 125           | 194           |
| Austria        |              | 3             | 20            | 30            | 42            | 79            | 95            | 139           |
| France         | 3            | 10            | 10            | 19            | 22            | 62            | 116           | 148           |
| Finland        | 6            | 8             | 12            | 17            | 38            | 38            | 39            | 41            |
| Turkey         |              | 0             | 0             | 9             | 9             | 19            | 19            | 19            |
| Luxembourg     |              | 2             | 2             | 5             | 10            | 15            | 15            | 16            |
| Norway         |              | 4             | 4             | 9             | 13            | 13            | 17            | 97            |
| Belgium        |              | 7             | 7             | 8             | 9             | 13            | 31            | 44            |
| Czech Republic |              | 7             | 7             | 7             | 12            | 12            | 12            | 12            |
| Russia         |              | 5             | 5             | 5             | 5             | 5             | 5             | 7             |
| Poland         |              | 1             | 3             | 3             | 5             | 5             | 28            | 28            |
| Switzerland    |              | 2             | 2             | 3             | 3             | 3             | 3             | 3             |
| Latvia         |              | 1             | 1             | 1             | 1             | 1             | 1             | 1             |
| Romania        |              | 0             | 0             | 1             | 1             | 1             | 1             | 1             |
| <b>Total</b>   | <b>2,506</b> | <b>3,506</b>  | <b>4,761</b>  | <b>6,464</b>  | <b>9,076</b>  | <b>13,258</b> | <b>17,528</b> | <b>23,225</b> |
| <b>Growth</b>  |              | <b>39.9 %</b> | <b>35.8 %</b> | <b>35.8 %</b> | <b>40.4 %</b> | <b>46.1 %</b> | <b>32.2 %</b> | <b>32.5 %</b> |

Table 39. Influence of Wind Power on the Electricity Demand in the Year 2030

| Annual Growth Rate                  | 10 % | 15 %   | 20 %  |
|-------------------------------------|------|--------|-------|
| Installed Capacity in GW until 2030 | 335  | 1,628  | 3,826 |
| Percentage of Maximum Load in 2030  | 49 % | 236 %  | 556 % |
| Wind Generation at 2000 h/a in TWh  | 670  | 3,256  | 7,652 |
| Percentage of Total Demand in 2030  | 15 % | 72.5 % | 170 % |

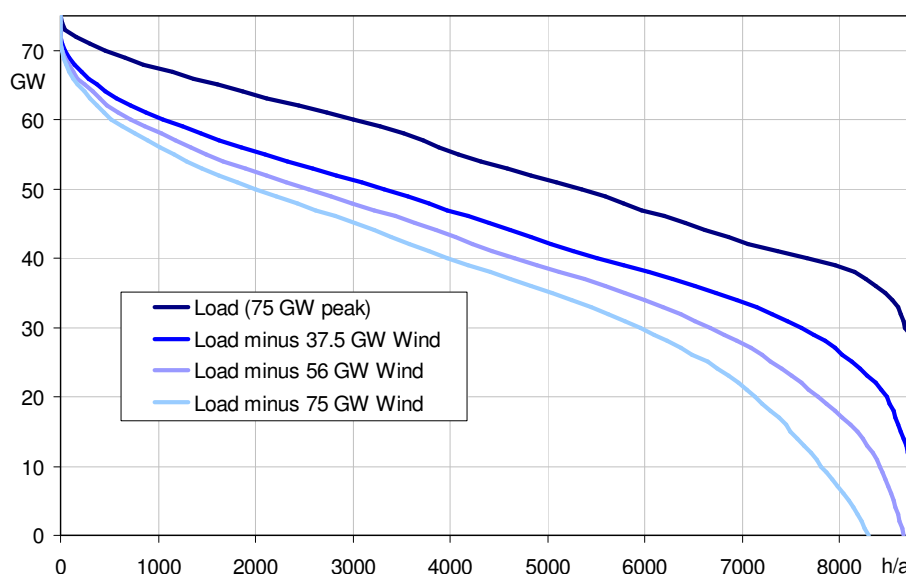


Figure 44. Influence of Different Wind Installation Numbers on Full Load Hours in Germany

The top line in Figure 44 shows the power level of the German load curve in dependence on the cumulated hours within a year meanwhile this power level is necessary. Base load is stated as the power level at the right edge of the graph at 8760 h/a: 28.3 GW. The other lines downward successively represent the remaining demand after installation of wind power plants with 37.5, 56 or 75 GW, distributed over whole Germany. It can be noticed clearly that the base load decreases significantly with high wind installations. For installations in the power range of 70% of the maximum demand (56 GW) no firm base load exists anymore. There may be some compensation effects for larger areas than the considered small German region. However, if the annual growth rates of wind power will remain between 10 and 15 %, base load with 8760 h/a will very probably become zero in the year 2030.

Although therefore base load scenarios for the year 2030 are not very realistic, they are calculated with the same power level as the state-of-the-art scenarios to give a comparison. Also for comparison purposes, the remaining load scenarios are calculated for power levels of 5 GW, 10 GW, 100 GW and 150 GW for the today as well as for the 2030 scenario.

#### 4.1.3 Definition of the Terrestrial Technologies for Power Supply

Necessary technologies for a terrestrial power supply from solar irradiation can be classified in the generation system, a system for energy storage for the case that demand and supply level are differing, as well as the transmission system, delivering the power to where it is needed in Europe. As generation system alternatively photovoltaic or Solar Thermal Power Plants have been selected. Solar Thermal Power Plants have the advantage that a thermal storage yet can be included easily. For the above-named technologies the technical assumptions followed by cost estimations are described for the state-of-the-art and subsequently for the future case.

### 4.1.3.1 Photovoltaic Generation System

For the state-of-the-art photovoltaic system a real existing panel and inverter type at contemporarily good qualities have been selected. Until 2020/2030 a technology change will take place. As the exact development is not known, no exact features will be chosen but only some general reasonable assumptions and suggestions be done.

#### 4.1.3.1.1 Technical Definitions for State-of-the-Art

The selected photovoltaic panel is a Sharp NT-185U1 panel with a peak power of 185 W (Table 40). Its cell efficiency is 17.5% with a resulting module efficiency of 14.2% at 1000 W/m<sup>2</sup> at 25°C. Part load efficiency as well as temperature coefficient have been respected within the simulation. As inverter a SMA Sunny Boy 1500 with an efficiency of 96% in a wide range is used.

Table 40. Technical Definition of the State-of-the-Art Photovoltaic Reference System

|                    |                                                                                                                                                                                                                                                                                                                                                                                                     |
|--------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>PV Module</b>   | Sharp NT-185U1 (185 W <sub>p</sub> )<br>Rated operating conditions: 36.21 V, 5.11 A, 185 W <sub>p</sub><br>Module dimensions: 1.575 x 0.826 m<br>Cell type: monocrystalline silicon<br>Cell efficiency: 17.5 %<br>Module Efficiency: 14.2% at 1000 W/m <sup>2</sup> and 25°C<br>Assumed Part load efficiency: 11.5% at 100 W/m <sup>2</sup> and 25°C<br>Temperature coefficient of power: -0.48%/°C |
| <b>PV Inverter</b> | SMA Sunny Boy 1500<br>Nominal AC Power: 1.5 kVA<br>Nominal DC Power: 1.56 kW<br>Efficiency at 100% load: 96 %<br>Efficiency at 50% load: 96 %<br>Efficiency at 10% load: 92 %                                                                                                                                                                                                                       |
| <b>PV System</b>   | Orientation V1: South, 30° tilt angle<br>Orientation V2: South, 10° tilt angle in summer, 60° tilt angle in winter<br>Number of modules per Inverter: 8<br>Number of parallel inverters: 677<br>Total rated power: 1 MWp<br>Losses due to dirt: 5 %<br>Other unexpected losses: 5 % (availability: 95 %)                                                                                            |

Eight modules are combined on one inverter with a number of 677 parallel inverters in complete to come to a total rated power of 1 MWp. The PV panels are inclined towards the south with two different collocation manners: a fix inclination angle of 30° over the whole year as orientation V1 or a flat tilt angle of 10° throughout the summer and a steeper tilt angle of 60° throughout the winter as orientation V2. The change will be done manually around equinox beside the normal cleaning process. For losses due to soiling of the panels 5% have been calculated generally with further losses of 5% e.g. showing an availability of 95%.

#### 4.1.3.1.2 Technical Definitions for 2020/2030

Until the years 2020/2030 most experts predict a change in the PV cell technology. What type exactly this 3<sup>rd</sup> generation cells will be is hard to say today, maybe thin film and/or multi junction cells. However, the type of cells does not matter for power generation, as the price in combination with its

efficiency will decide. The 3<sup>rd</sup> generation technology however will hardly show higher efficiencies but be significantly cheaper. Inverter and system specifications will be increased slightly. The technical definitions are listed in Table 41.

Table 41. Technical Definition of the Photovoltaic Reference System

|                    |                                                                                                                                                                          |
|--------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>PV Module</b>   | 3 <sup>rd</sup> generation PV cells<br>Cell type: e.g. multi junction solar cells<br>Cell efficiency: >20 %<br>Module Efficiency: 20 % at 1000 W/m <sup>2</sup> and 25°C |
| <b>PV Inverter</b> | Increased Inverter efficiency by 2 %<br>compared to state-of-the art inverter                                                                                            |
| <b>PV System</b>   | Orientation V1: South, 30° tilt angle<br>Orientation V2: South, 10° tilt angle in summer, 60° tilt angle in winter<br>Other unexpected losses: 2 % (availability: 98 %)  |

The result of the assumptions is a 5 % higher hourly and annual system output per kW<sub>p</sub> and a significantly reduced surface demand.

The future efficiency of PV systems is hard to estimate today. However, it is not really important for the scenario calculated here, because the efficiency only influences the needed area. The output per kW<sub>p</sub> is not influenced by the PV module efficiency. Since we assume that PV systems are only installed in desert regions with nearly free land availability the real system efficiency has no impact on the results.

#### 4.1.3.1.3 Cost Estimations for State-of-the-Art

The total investment costs for the installation of 1 kW<sub>p</sub> PV cells today are assumed to be 4,500 € for panels with orientation V1. For PV with orientation V2 2% higher investment costs are assumed. The globally installed capacity today is about 2 GW<sub>p</sub>. So far PV showed a relatively constant cost reduction progress ratio between 0.8 and 0.82 over the last decades [IEA00; Wod00]. In other words, if the cumulative installed capacity doubles, the costs decrease by 18 to 20%. Many experts assume that these progress ratios can continue until a further 50% price reduction for crystalline cell technologies. A lower price reduction of 0.92 is assumed for crystalline cell technologies afterwards. As annual operation and maintenance costs for orientation V1 2.2% were estimated and 2.7% for V2. The data is listed in Table 42

Table 42. Assumptions for Cost Estimations for State-of-the-Art PV Systems

|                  |                                                                                                                                                                                                                                                                                                                               |
|------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>PV System</b> | Total investment costs (turnkey): 4,500 €/kW <sub>p</sub> (2 GW <sub>p</sub> installed cap.)<br>2% higher investment costs for orientation V2<br>Progress ratio: 0.82 until 50% cost reduction, then 0.92<br>Lifetime: 25 years<br>O&M Costs: 2.2% of investment costs p.a. for orientation V1 and<br>2.7% for orientation V2 |
|------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

Further cost reductions can be achieved by the introduction of new cell technologies. Therefore, for the time frame 2020/2030 it is assumed that a continuous progress ratio of 0.8 is possible. The investment costs for the crystalline and also the 3<sup>rd</sup> generation PV cells are graphically illustrated in Figure 45 in



dependence on the global installed capacity. The capacity for the global installation was assumed to be:

$$\text{Global installation} = 2 \text{ GW}_p + 2 \times \text{Installation within scenario}$$

The new installation of high numbers of new PV systems causes a costs reduction and therefore initialises further installations throughout the world, resulting in a higher global demand. Therefore the installation numbers within the scenario are doubled for estimating the resulting costs. Table 43 lists the detailed prices and the assumed global installation capacity for several installation numbers. For installation capacities of 1 TW for European power supply, prices are assumed to go down on about 1,300 €/kW<sub>p</sub>.

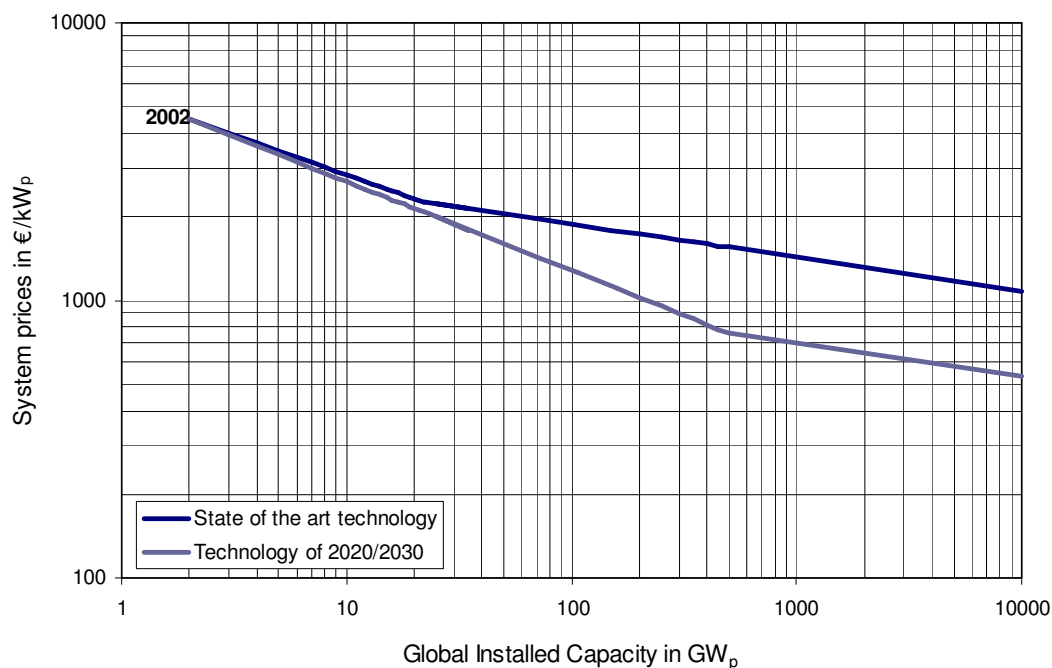


Figure 45. Assumptions for PV turnkey installation costs

Table 43. Assumptions for Investment Costs for different state-of-the-art PV Installation Numbers

| Installation within Scenario         | Assumed global installation | Investment costs        |
|--------------------------------------|-----------------------------|-------------------------|
| 0 GW <sub>p</sub> <sup>V1)</sup>     | 2.0 GW <sub>p</sub>         | 4,500 €/kW <sub>p</sub> |
| 2.9 GW <sub>p</sub> <sup>V1)</sup>   | 7.8 GW <sub>p</sub>         | 3,048 €/kW <sub>p</sub> |
| 3 GW <sub>p</sub> <sup>V1)</sup>     | 8.0 GW <sub>p</sub>         | 3,026 €/kW <sub>p</sub> |
| 3.5 GW <sub>p</sub> <sup>V1)</sup>   | 9.0 GW <sub>p</sub>         | 2,925 €/kW <sub>p</sub> |
| 4 GW <sub>p</sub> <sup>V1)</sup>     | 10.0 GW <sub>p</sub>        | 2,839 €/kW <sub>p</sub> |
| 33 GW <sub>p</sub> <sup>V1)</sup>    | 68.0 GW <sub>p</sub>        | 1,970 €/kW <sub>p</sub> |
| 39 GW <sub>p</sub> <sup>V2)</sup>    | 80.0 GW <sub>p</sub>        | 1,932 €/kW <sub>p</sub> |
| 65 GW <sub>p</sub> <sup>V2)</sup>    | 132.0 GW <sub>p</sub>       | 1,855 €/kW <sub>p</sub> |
| 77 GW <sub>p</sub> <sup>V2)</sup>    | 156.0 GW <sub>p</sub>       | 1,783 €/kW <sub>p</sub> |
| 653 GW <sub>p</sub> <sup>V2)</sup>   | 1,308 GW <sub>p</sub>       | 1,380 €/kW <sub>p</sub> |
| 829 GW <sub>p</sub> <sup>V2)</sup>   | 1,660 GW <sub>p</sub>       | 1,341 €/kW <sub>p</sub> |
| 997 GW <sub>p</sub> <sup>V2)</sup>   | 1,996 GW <sub>p</sub>       | 1,312 €/kW <sub>p</sub> |
| 1,243 GW <sub>p</sub> <sup>V2)</sup> | 2,488 GW <sub>p</sub>       | 1,278 €/kW <sub>p</sub> |

V1) Orientation V1, 30° tilt angle, south oriented

V2) Orientation V2, 10° tilt angle in summer, 60° tilt angle in winter plus 2% higher investment costs

#### 4.1.3.1.4 Cost Estimations for 2020/2030

As pointed out in section 4.1.3.1.3, further price reductions should be possible with the introduction of a new cell technology. The initial pricing of the new technology is assumed to be the same as for the state-of-the-art cells with 4,500 €/kW<sub>p</sub>, but its progress ratio of 0.8 is estimated to continue decreasing until a global installation of 500 GW<sub>p</sub> will be reached, then turning to a ratio of 0.92 (see Table 44 and the lower curve in Figure 45). With ongoing learning effects, the operation and maintenance costs of the future PV system will drop to 1.5% of the investment costs per year for orientation V1 and to 2% for orientation V2.

Table 44. Assumptions for Cost Estimations for future PV Systems in 2020/2030

|                  |                                                                                                                                                                                                                                                                                                                                                        |
|------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>PV System</b> | <p>Total investment costs (turnkey): 4,500 €/kW<sub>p</sub> (2 GW<sub>p</sub> installed cap.)</p> <p>2 % higher investment costs for orientation V2</p> <p>Progress ratio: 0.8 and 0.92 for &gt;500 GW<sub>p</sub></p> <p>Lifetime: 25 years</p> <p>O&amp;M Costs: 1.5% of investment costs p.a. for orientation V1</p> <p>2.0% for orientation V2</p> |
|------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

For calculation of the resulting prices of photovoltaic in 2020/2030, the globally installed PV capacity has to be estimated. With growth rates of 10 to 20%, the following capacities are expected to be installed by 2025 yet without the impact of this scenario:

- 10 % growth rate p.a.: 21.7 GW<sub>p</sub>
- 15 % growth rate p.a.: 65.8 GW<sub>p</sub>
- 20 % growth rate p.a.: 190.8 GW<sub>p</sub>

Finally, 100 GW<sub>p</sub> with a growth rate between 15 and 20% have chosen to estimate the installation between 2020 and 2030 without the impact of this scenario. These growth rates are slightly below current values. It is also assumed that the high installation numbers of this scenario will cause further installations at other sites on the earth in the same order. Thus, the assumed installation numbers are calculated along:

$$\text{Global installation} = 100 \text{ GW}_p + 2 \times \text{Installation within scenario}$$

Total investment costs as well as the resulting global installations are listed for several installation capacities within the scenario with future technology in Table 45.

Table 45. Assumptions for Investment Costs for several PV Installation Numbers of the future technology

| Installation within Scenario         | Assumed global installation | Investment costs        |
|--------------------------------------|-----------------------------|-------------------------|
| 0 GW <sub>p</sub> <sup>V1)</sup>     | 100 GW <sub>p</sub>         | 1,277 €/kW <sub>p</sub> |
| 3 GW <sub>p</sub> <sup>V1)</sup>     | 106 GW <sub>p</sub>         | 1,253 €/kW <sub>p</sub> |
| 30 GW <sub>p</sub> <sup>V1)</sup>    | 160 GW <sub>p</sub>         | 1,098 €/kW <sub>p</sub> |
| 33 GW <sub>p</sub> <sup>V2)</sup>    | 166 GW <sub>p</sub>         | 1,085 €/kW <sub>p</sub> |
| 55 GW <sub>p</sub> <sup>V2)</sup>    | 220 GW <sub>p</sub>         | 991 €/kW <sub>p</sub>   |
| 67 GW <sub>p</sub> <sup>V2)</sup>    | 234 GW <sub>p</sub>         | 971 €/kW <sub>p</sub>   |
| 553 GW <sub>p</sub> <sup>V2)</sup>   | 1,206 GW <sub>p</sub>       | 684 €/kW <sub>p</sub>   |
| 704 GW <sub>p</sub> <sup>V2)</sup>   | 1,508 GW <sub>p</sub>       | 666 €/kW <sub>p</sub>   |
| 846 GW <sub>p</sub> <sup>V2)</sup>   | 1,792 GW <sub>p</sub>       | 652 €/kW <sub>p</sub>   |
| 1,056 GW <sub>p</sub> <sup>V2)</sup> | 2,212 GW <sub>p</sub>       | 636 €/kW <sub>p</sub>   |

V1) Orientation V1, 30° tilt angle, south oriented

V2) Orientation V2, 10° tilt angle in summer, 60° tilt angle in winter, plus 2% investment costs

#### 4.1.3.2 Solar Thermal Generation System

As solar thermal generation system on principle three types of generation system are possible: parabolic trough solar collectors, solar power towers or parabolic dishes. Parabolic trough systems is said to be the most mature technique. 354 MW of this type yet exist in the Californian Mojave desert producing electricity since the end 1980's without serious problems or failures (Figure 46). For the solar power tower concept several projects with different technologies were running for several years with power levels of several MW proofing also technical maturity of this technology. Both of these technologies are valid to be installed for bigger power levels. The third option, the parabolic dishes, as the size of one unit will be within several to several hundred kW, they are better suited for smaller power levels, especially for off grid solutions.



Figure 46. Solar Thermal Trough Power Plant in Kramer Junction, USA

#### 4.1.3.2.1 Technical Definitions for State-of-the-Art

As the solar thermal trough is the most mature technology with the availability of reliable technical data, this type of solar thermal power plant has been chosen for the solar thermal scenario. Figure 47 shows the functional principle of such a power plant: Generally it is similar to that of a conventional power plant with the exception that generation and heating of steam is not done by burning fossil fuel or heat released by nuclear fission but with solar energy. Therefore solar irradiation is captured by large mirrors with parabolic shape (the troughs) and concentrated on absorber tubes, where the irradiation is converted to heat. The absorber tubes are mounted in the focusing line of the troughs. The heat is passed to a heat transfer medium, which in turn serves to heat the steam via heat exchanger. Additionally, a storage equipment can be adjoined to preserve exceeding heat for hours without irradiation, improving over-all efficiency and availability of the plant.

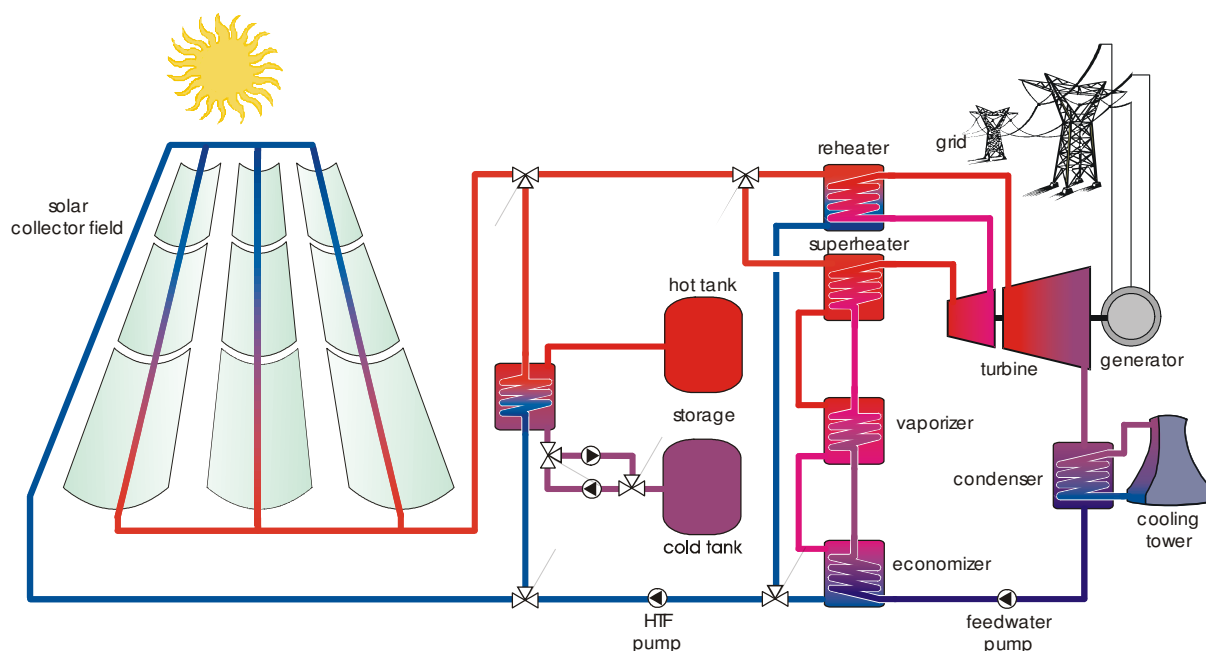


Figure 47. Layout of a Solar Thermal Trough Power Plant

Exact specifications of the selected solar trough power plant are listed in Table 46: As collector the newly developed Eurotrough-2 collector with ultra high vacuum absorber tube with an optical efficiency of 76% is selected. With an effective mirror area of 545 m<sup>2</sup> an efficiency of nearly 66% is reached at a direct normal irradiance of 800 W/m<sup>2</sup> and a temperature lift of 400 K. The size of the collector field was variable and has been optimized for the corresponding scenario (power level, plant size, storage seizing). As fluid through the absorber tubes of the plant thermal oil was used. Losses of the collector field due to soiling were 5% and the availability of the power plant 99%. For the power block a Rankine steam turbine cycle was chosen with a net output of 96 MW<sub>e</sub> and a gross efficiency of 39%. Furthermore, the power plant was equipped with thermal storage consisting of two tanks with molten salt as storage medium. The volume of the storage equipment has been optimized according to the respective scenario.

Table 46. Technical Definition of the State-of-the-Art Reference Solar Thermal Trough Power Plants.

|                        |                                                                                                                                                                                                                              |
|------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Collector</b>       | Eurotrough-2 100m, UVAC absorber tube<br>optical efficiency: 75.9 %<br>Aperture width: 5.76 m<br>Effective mirror area: 545 m <sup>2</sup><br>efficiency at 800 W/m <sup>2</sup> and $\Delta T=400^{\circ}\text{C}$ : 65.5 % |
| <b>Collector Field</b> | Size variable, depending on scenario<br>HFT fluid: VP1 thermal oil<br>Availability: 99 %<br>Average mirror cleanliness: 95 %<br>Average nominal field temperature: 340°C                                                     |
| <b>Power Block</b>     | Rankine steam turbine cycle<br>95.5 MW net<br>39.0% gross efficiency                                                                                                                                                         |
| <b>Thermal storage</b> | Two tank molten salt<br>Size variable, depending on scenario                                                                                                                                                                 |

#### 4.1.3.2.2 Technical Definitions for 2020/2030

Ongoing development in solar thermal power plants promises further improvement of the technology respectively its efficiency. In the case of solar troughs new attempts go for the replacement of the thermal oil as heat transfer medium by direct water steam generation, but also new power tower concepts show promising results. However, no simulation tool exists to simulate solar thermal power plants with combined cycle. Finally, the technical calculations of the future scenario have been performed along the modelling of the state-of-the-art scenario with the change of an increased efficiency to over 20%. The cost estimations also assume an increase in the efficiency. To be comparable with the PV calculations a 5 % decrease in effective mirror area and storage size has been assumed, too.

Table 47. Technical Definition of the Solar Thermal Reference Systems.

|                              |                                                                                                                                                            |
|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Solar Thermal Systems</b> | Improved solar thermal trough power plants<br>or high-efficiency solar thermal tower power plants using combined cycles<br>with overall efficiencies >20 % |
|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|

#### 4.1.3.2.3 Cost Estimations for State-of-the-Art

Today costs of 225 € per square meter of effective collector area have to be considered for the collector field, the price for the thermal oil as heat transfer fluid yet included. The power block is computed for 800 €/kW<sub>el</sub> and additional 30 €/kW<sub>th</sub> have to be assessed for thermal storage. According to [Ene99] a progress rate of 0.88 can be estimated for the total costs at first, changing to 0.96 after installation of 500 million m<sup>2</sup> of effective collector area. Today's installed effective solar collector mirror area is about 2.3 million m<sup>2</sup>. It is assumed that a part of the learning curve had to be made again, because no new solar thermal power plants have been built since 1991. Therefore, a reference mirror area of 3.5 million m<sup>2</sup> for the learning process was assumed. In contrast to PV

systems no significant installation numbers are planned outside Europe or North Africa today. Therefore, it is assumed that the total installed capacity is only used to cover the demand in the scenario. Finally the following assumptions are made for global installation capacity:

$$\text{Global installation} = 2.3 \text{ million m}^2 + \text{Installation within scenario}$$

The key parameters of today's solar trough power plant costs are listed in Table 48. Table 49 a detailed list is presented of the percentage of the initial costs after application of the progress ratio in dependence on the installed capacity within this scenario and its corresponding global installation numbers. This course of the percentage of the total investment costs in dependence on the global installations is graphically illustrated in Figure 48. Here it is referred to the percentage and not to real costs because in contrary to photovoltaic the initial costs of the solar thermal power plant vary with the optimized size of the collector field and connected to this the necessary storage dimensions.

Table 48. Assumptions for Cost Estimations for State-of-the-Art Solar Thermal Systems

|                           |                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
|---------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Trough Power Plant</b> | <p>Total investment costs (turnkey) referred to 340 MW installed cap.</p> <p>225 €/m<sup>2</sup> effective collector area incl. HTF</p> <p>800 €/kW<sub>el</sub> power block size</p> <p>30 €/kW<sub>th</sub> thermal storage size</p> <p>progress ratio: 0.88 <sup>[Ene99]</sup> applied to 3.5 million m<sup>2</sup></p> <p>and 0.96 for &gt;500 million m<sup>2</sup></p> <p>Lifetime: 25 years</p> <p>O&amp;M costs: 2.9 % of investment costs p.a.</p> |
|---------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

Table 49. Assumptions for Investment Costs for different ST Installation Numbers

| Installation within Scenario   | Assumed global installation    | Investment costs |
|--------------------------------|--------------------------------|------------------|
| 0 million m <sup>2</sup>       | 2.3 million m <sup>2</sup>     | 100.0%           |
| 1.2 million m <sup>2</sup>     | 3.5 million m <sup>2</sup>     | 100.0%           |
| 16.2 million m <sup>2</sup>    | 18.5 million m <sup>2</sup>    | 73.6%            |
| 17.8 million m <sup>2</sup>    | 20.1 million m <sup>2</sup>    | 72.4%            |
| 18.0 million m <sup>2</sup>    | 20.3 million m <sup>2</sup>    | 72.3%            |
| 20.2 million m <sup>2</sup>    | 22.5 million m <sup>2</sup>    | 71.7%            |
| 180.2 million m <sup>2</sup>   | 182.5 million m <sup>2</sup>   | 48.2%            |
| 220.0 million m <sup>2</sup>   | 222.3 million m <sup>2</sup>   | 46.5%            |
| 367.5 million m <sup>2</sup>   | 369.8 million m <sup>2</sup>   | 42.3%            |
| 437.6 million m <sup>2</sup>   | 439.9 million m <sup>2</sup>   | 41.0%            |
| 3,556.5 million m <sup>2</sup> | 3,558.8 million m <sup>2</sup> | 35.7%            |
| 4,387.7 million m <sup>2</sup> | 4,390.0 million m <sup>2</sup> | 35.2%            |
| 5,216.2 million m <sup>2</sup> | 5,218.5 million m <sup>2</sup> | 34.9%            |
| 6,582.7 million m <sup>2</sup> | 6,585.0 million m <sup>2</sup> | 34.4%            |

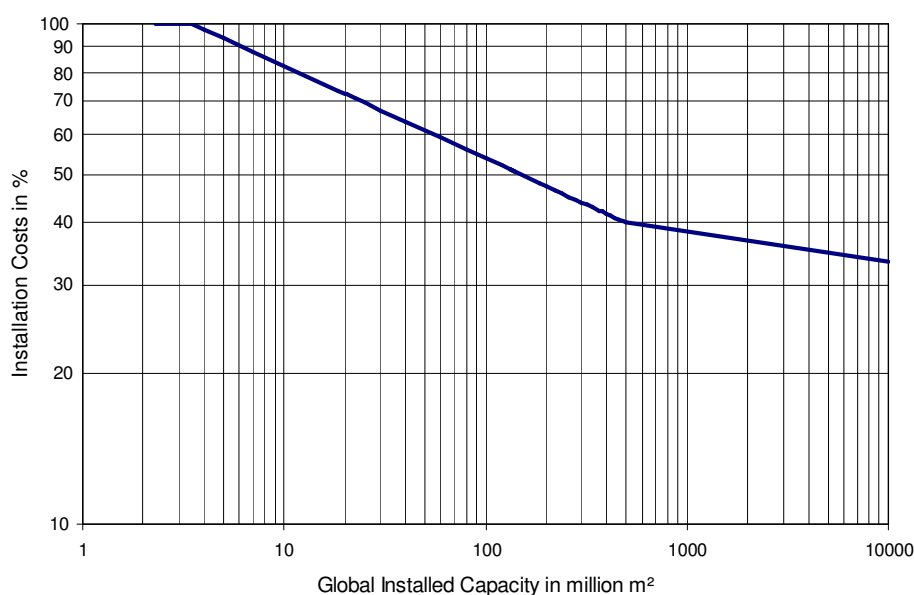


Figure 48. Assumptions for Solar thermal turnkey installation costs

#### 4.1.3.2.4 Cost Estimations for 2020/2030

In contrary to the scenario for today's installation, a multiplication effect when installing a high number of solar thermal systems is assumed. Since the suited areas for solar thermal power plants are



only in the Sunbelt of the earth, the factor 1.5, which is lower than for PV, have been chosen. Furthermore, it was assumed that 100 million m<sup>2</sup> of effective collector area will be installed anyhow until 2020/2030. Thus the globally installed capacity is calculated along:

$$\text{Global installation} = 100 \text{ million m}^2 + 1.5 \times \text{Installation within scenario}$$

Further additional cost reductions more than within the progress ration are not considered. The resulting reduction of investment costs for a list of increasing installation numbers within this scenario as well as the corresponding global installation capacities are presented in Table 50.

Table 50. Assumptions for Investment Costs for different ST Installation Numbers.

| Installation within Scenario   | Assumed global installation    | Investment costs |
|--------------------------------|--------------------------------|------------------|
| 0 million m <sup>2</sup>       | 100 million m <sup>2</sup>     | 53.9 %           |
| 16.4 million m <sup>2</sup>    | 132.8 million m <sup>2</sup>   | 51.1 %           |
| 168.9 million m <sup>2</sup>   | 353.4 million m <sup>2</sup>   | 42.7 %           |
| 201.9 million m <sup>2</sup>   | 402.9 million m <sup>2</sup>   | 41.7 %           |
| 340.1 million m <sup>2</sup>   | 610.2 million m <sup>2</sup>   | 39.6 %           |
| 401.6 million m <sup>2</sup>   | 702.4 million m <sup>2</sup>   | 39.3 %           |
| 3,107.8 million m <sup>2</sup> | 4,761.7 million m <sup>2</sup> | 35.1 %           |
| 4,027.0 million m <sup>2</sup> | 6,140.5 million m <sup>2</sup> | 34.5 %           |
| 4,684.2 million m <sup>2</sup> | 7,126.3 million m <sup>2</sup> | 34.2 %           |
| 6,041.6 million m <sup>2</sup> | 9,162.4 million m <sup>2</sup> | 33.7 %           |

### 4.1.3.3 Definitions of Storage Systems

A variety of different possibilities and systems exist for storing energy. Within the here investigated scenarios of up to a full European electricity supply, large storage capacities are needed with a range from hourly or daily until maybe even seasonal storage. Feasible and over all cheap solutions are necessary though. For a direct storage of electricity no practical solution exists, so electricity must be converted to other forms of energy for easier storing. Possible solutions are e.g. pumped hydroelectric storage, Compressed Air Energy Storage (CAES) or conversion to chemically bound forms of energy like e.g. the production of hydrogen. Hydrogen storage systems are suitable for large storage capacities and low power demand, e.g. for seasonal storage. However, the efficiency of the hydrogen storage chain of first hydrogen production and a subsequent reconversion to electricity is rather low. With storage efficiencies in the range of 70%, CAES is a real alternative to hydrogen storage and can lower the costs especially of the PV scenarios. But finally, taking the price into account it is economically reasonable to cover the necessary storage capacity as far as possible either by pumped hydroelectric storage and/or by over-dimensioned solar systems.

For solar thermal power plants storage is far easier as in any case the irradiation is primarily converted to heat at the collector. Thus short-time thermal storage is adequate and already implemented with capacities of several hours up to days. For seasonal storage at large power levels huge capacities would be necessary and better thermal insulation with low heat losses required.

Fortunately, as will be shown in paragraph 4.2 and 4.3, seasonal storage could be avoided by intelligent configuration of the generation systems. Thus, expensive storage systems like e.g. hydrogen storage can be avoided, too. Nevertheless the production of hydrogen by using solar energy has been examined for comparison purposes in the combined space-terrestrial scenario of paragraph 5 and as a stand-alone case within paragraph 5.8. Compressed Air Energy Storage (CAES) systems have not been considered because no reliable technical and economical data for this storage technology is available.

#### 4.1.3.3.1 Pumped hydroelectric storage

Like for the power generation systems the technical specifications of the storage systems are presented in the following section at first for the state-of-the-art and subsequently for the future scenario, followed by their cost assumptions.

##### 4.1.3.3.1.1 Technical definitions state-of-the-art pumped hydro storage

Table 51 gives an impression of actually installed storage capacities and its corresponding power levels in some countries of the supply zones. With 18.4 TWh Spain has the highest capacity, followed by France, Switzerland and Italy, which have about half of the Spanish capacity.

Table 51. Installed Power and Storage Capacity of Reservoirs and Mixed Pumped Storage [Leh01].

| Zone | Country     | Installed Power Capacity in GW | Storage Capacity in TWh |
|------|-------------|--------------------------------|-------------------------|
| D    | Germany     | 1.4                            | 0.3                     |
| E    | Spain       | 7.7                            | 18.4                    |
| E    | Portugal    | 2.1                            | 2.6                     |
| F    | France      | 11.6                           | 9.8                     |
| G    | Greece      | 2.3                            | 2.4                     |
| I    | Italy       | 7.4                            | 7.9                     |
| S    | Austria     | 5.4                            | 3.2                     |
| S    | Switzerland | 9.5                            | 8.4                     |

Taking a look at the necessary power levels and capacity in paragraphs 4.2, 4.3 and 5, it can be noted that for higher power levels of demand supply the installed power capacity within these countries is far to low. Respective the listed energy storage capacities, Table 51 includes reservoirs as well as mixed pumped storage whereas needed here is not only a reservoir of the stated size but water needs to be exchanged completely between an upper and a lower basin to access the necessary amount of energy. Therefore within these scenarios it is assumed that the storage capacity is built newly in the generation zones as land availability is given and land prices are lower there. Especially for energy generation in Zone 3 pumped hydroelectric storage seems perfectly suited as in the Eastern part of Egypt beside the Red Sea a mountainous landscape can be found with altitudes of a few hundred until up to about 2000 m. The construction of pumped hydropower is well known and data available.

Technical data of the used pumped hydroelectric storage plant is listed in Table 52: the data refers to a storage plant in a unit size of 6 GWh with a maximal power of 1 GW, a charge-discharge efficiency of 75%, and an assumed difference in altitude of 400 metres.

To get an impression of the dimensions of the necessary storage sizes calculated within the scenarios here: with maximal capacities at full supply ranging from 3,5 TWh for base load, 6 TWh for remaining load to 12,5 TWh for complete supply within the combined scenario, the reservoir accounts for sizes between 3 and 11 billion m<sup>3</sup> (or tons) of water, meaning a cubic box with a side length of between 1500 to 2200 m.

Table 52. Technical Definition of Pumped Hydroelectric Storage

|                       |                                                                 |
|-----------------------|-----------------------------------------------------------------|
| <b>Pumped Storage</b> | 1 GW, 6 h full load (6 GWh)<br>Charge-Discharge Efficiency: 75% |
|-----------------------|-----------------------------------------------------------------|

#### 4.1.3.3.1.2 Technical Definitions for 2020/2030

The progress of technology will account for larger storage plants with higher power levels and better efficiencies. Therefore assumed for the years 2020/2030 are storage plants of the size of 24 GWh and 4 GW maximal power with a charge-discharge efficiency of 85% (Table 53).

Table 53. Technical Definition of Pumped Hydroelectric Storage

|                       |                                                                   |
|-----------------------|-------------------------------------------------------------------|
| <b>Pumped Storage</b> | 4 GW, 6 h full load (24 GWh)<br>Charge-Discharge Efficiency: 85 % |
|-----------------------|-------------------------------------------------------------------|

#### 4.1.3.3.1.3 Cost Estimations for State-of-the-Art

The costs for pumped hydroelectric storage plants have to be accounted for two separated systems: the construction of the reservoir basin with its corresponding dimensions and the technical part with its charge-discharge system. Along data from [Sch01] and own further assumptions for the basin investment costs of 14 €/kWh are estimated and for the technical part 700 €/kW. Furthermore, a lifetime of 40 years is assumed for the plant. For operation and maintenance 6 €/MWh were calculated.

Table 54. Assumptions for Cost Estimations for State-of-the-Art Storage Systems.

|                     |                                                                                   |
|---------------------|-----------------------------------------------------------------------------------|
| <b>Pumped Hydro</b> | Investment costs: 14 €/kWh + 700 €/kW<br>Lifetime: 40 years<br>O&M costs: 6 €/MWh |
|---------------------|-----------------------------------------------------------------------------------|

DATA: [SCH01], OWN ASSUMPTIONS

#### 4.1.3.3.1.4 Cost Estimations for 2020/2030

For the future storage system a price reduction of 15% was assumed. Hence, investment costs for the basin account for 12 €/kWh and 600 €/kW for the charge-discharge system. Operation and maintenances costs are estimated to be able to be lowered to 4 €/MWh.

Table 55. Assumptions for Cost Estimations for 2020/2030 Storage Systems [Sch01].

|                     |                                                                                                   |
|---------------------|---------------------------------------------------------------------------------------------------|
| <b>Pumped Hydro</b> | Investment costs: 12 €/kWh + 600 €/kW (15% reduction)<br>Lifetime: 40 years<br>O&M costs: 4 €/MWh |
|---------------------|---------------------------------------------------------------------------------------------------|

#### 4.1.3.3.2 Hydrogen storage

For hydrogen production different assumptions were made for the two differing cases of:

- 1) Hydrogen storage within the combined space-terrestrial power supply scenario (paragraph 5), and
- 2) Solar based production of hydrogen (paragraph 5.8).

As the space solution will not be available today, hydrogen storage for the combined scenario is set up only for the years of 2020/2030. The assumptions taken for solar based production of hydrogen are presented as an independent package in paragraph 5.8.

##### 4.1.3.3.2.1 Technical definitions for a future hydrogen storage scenario

Hydrogen and oxygen is produced by electrolysis with an efficiency of the electrolyser of 65% including the AC/DC converters, pumps, blowers and the control unit. Hydrogen is stored in spherical steel pressure vessels of a volume of 3,000 m<sup>3</sup>. At a maximal pressure of 2 MPa the pressure vessel captures 49,300 m<sup>3</sup> of hydrogen. Because the electrolyser delivers hydrogen at a pressure above 2 MPa, no additional compressor is required. Re-conversion of hydrogen to electricity is done by fuel cells or by burning it in a combined cycle gas turbine with an efficiency of 55%. Hence, the overall efficiency of the storage chain is around 36%. Detailed technical data is listed in Table 56.

Table 56. Technical definitions of a future hydrogen storage and re-conversion system.

|                     |                                                                                                                                                   |
|---------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Electrolysis</b> | Efficiency: 65% (LHV)                                                                                                                             |
| <b>Storage</b>      | Spherical pressure vessels<br>Pressure range: 0.2 to 2.0 MPa<br>Volume: 3,000 m <sup>3</sup><br>Storage capacity: 49,300 Nm <sup>3</sup> hydrogen |
| <b>Reconversion</b> | Fuel Cell or Combined Cycle Gas Turbine<br>Efficiency: 55%                                                                                        |
| <b>Chain</b>        | Overall efficiency: 36%                                                                                                                           |

##### 4.1.3.3.2.2 Cost estimations for a future hydrogen storage scenario

The cost estimations of the hydrogen storage equipment is listed in Table 57: Investment costs of the electrolyzer are assumed to be 500 € per kW of power of produced hydrogen, corresponding operation and maintenance costs 1.5% of the overall investment costs. For the pressure storage vessel 1.92 million € are estimated per each unit. Finally, for the re-conversion equipment, 500 €/kW<sub>e</sub> of investment costs and 0.01 € per produced kWh<sub>e</sub> are assumed. A lifetime of 30 years is estimated for each of the components.

Table 57. Cost assumptions for the future hydrogen storage and re-conversion system.

|                                             |                                                                     |
|---------------------------------------------|---------------------------------------------------------------------|
| <b>Electrolyzer</b>                         | Investment costs: 500 €/kWhydrogen<br>O&M costs: 1.5% of investment |
| <b>Storage</b>                              | 1.92 million € per pressure vessel                                  |
| <b>Reconversion</b>                         | Investment costs: 500 €/kWe<br>O&M costs: 0.01 €/kWe                |
| Lifetime of each single component: 30 years |                                                                     |

#### 4.1.3.4 Definitions of Transmission Systems

The electricity generated in North Africa is transmitted to the supply zones in Europe via the three high voltage DC transmission lines T1, T2 and T3 as illustrated in Figure 40. The technical and economical data of the transmission lines will be presented in the next paragraphs, followed by a detailed description of the nature of the distribution system and basic assumptions for the calculation of the entire transportation distances.

##### 4.1.3.4.1 Technical definitions for the state-of-the-art transmission lines

For connection of the storage plants to the power plants, standard AC double lines with a voltage of 1,150 kV are used (Table 58). They show losses of 4.4% per 1,000 km. The subsequent transport of the electricity to the supply zones is done with DC double dipole lines at a voltage of 600 kV. Today their transmission capacity is 5 GW and shows losses in the range of 3.3% per 1,000 km. Additionally a station for conversion of AC to DC and a second for re-conversion is necessary with losses of 0.7% each of them.

Table 58. Technical definition for terrestrial power transmission [Czi99].

|                                |                                                                                                                                                                    |
|--------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Transmission HVDC Lines</b> | 600 kV HV DC double dipole<br>Transmission Capacity: 5 GW<br>Transmission losses: 3.3%/1000 km<br>Transmission losses in HVDC station ( $2 \times 0.7\% = 1.4\%$ ) |
| <b>Transmission HVAC Lines</b> | 1,150 kV HV AC double line<br>Transmission losses: 4.4%/1000 km                                                                                                    |

##### 4.1.3.4.2 Technical definitions of transmission lines in 2020/2030

Until the years 2020/2030 it is estimated that technical progress will lead to HV DC lines with a transportation capacity of 6.5 GW at 800 kV. Transmission losses are therefore assumed to be reduced to 2.5% per 1000 km and 0.5% for the AC-DC respectively DC-AC conversion. As the technology of the AC lines is yet widely developed, no further technical improvement is assumed until 2020/2030 but only cost reductions.

Table 59. Technical definition for terrestrial power transmission in 2020/2030 [Czi99].

|                                |                                                                                                                                                           |
|--------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Power Lines</b>             | 800 kV HV DC double dipole<br>Transmission Capacity: 6.5 GW<br>Transmission losses: 2.5%/1000 km<br>Transmission losses in HVDC station (2 x 0.5% = 1.0%) |
| <b>Transmission HVAC Lines</b> | 1,150 kV HV AC double line<br>Transmission losses: 4.4%/1000 km                                                                                           |

#### 4.1.3.4.3 Cost estimations of the state-of-the-art transmission lines

The costs of state-of-the-art HV AC transmission lines is at 200 million € per GW for a length of 1,000 km. The investment costs for DC lines refer to single power capacities of 5 GW and therefore account with 300 million € per 1,000 km to a lower price per GW compared to the AC lines. However, the DC lines have to be built in entire units of 5 GW and additional costs arise with two necessary AC/DC conversion stations for each line with further costs of 350 million €. A progress rate of both types of transmission lines is estimated for 0.96, starting at a reference distance of 10,000 km. Furthermore, annual operation and maintenance costs of 1% of the investment have to be taken into consideration. The lifetime of both types is assumed to be 25 years.

Table 60. Assumptions for cost estimations for state-of-the-art transmission lines [ICF02].

|                                |                                                                                                                                                                                                                       |
|--------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Transmission HVDC Lines</b> | Investment costs: 300 million €/1000 km (5 GW)<br>HVDC-Station: 2 x 350 million € (5 GW)<br>Lifetime: 25 years<br>O&M costs: 1% p.a. of investment costs<br>Progress ratio: 0.96 (starting at 10,000 km as reference) |
| <b>Transmission HVAC Lines</b> | Investment costs: 200 million €/1000 km/GW<br>Lifetime: 25 years<br>O&M costs: 1% p.a. of investment<br>Progress ratio: 0.96 (starting at 10,000 GW km as reference)                                                  |

In Table 61 the specific investment costs per 1,000 km as well as the costs per HV DC conversion station are listed for several lengths of transmission line installation within this scenario.

Table 61. Assumptions for today's investment costs for several lengths of HV DC transmission lines.

| Installation within Scenario | Costs per 1,000 km | Costs per HVDC-Station |
|------------------------------|--------------------|------------------------|
| <10,000 km                   | 0.300 billion €    | 0.700 billion €        |
| 12,200 km                    | 0.296 billion €    | 0.692 billion €        |
| 14,600 km                    | 0.293 billion €    | 0.685 billion €        |
| 29,100 km                    | 0.282 billion €    | 0.657 billion €        |
| 121,400 km                   | 0.259 billion €    | 0.604 billion €        |
| 140,600 km                   | 0.257 billion €    | 0.599 billion €        |
| 196,900 km                   | 0.252 billion €    | 0.587 billion €        |
| 219,300 km                   | 0.250 billion €    | 0.584 billion €        |
| 290,700 km                   | 0.246 billion €    | 0.574 billion €        |
| 436,000 km                   | 0.240 billion €    | 0.560 billion €        |

#### 4.1.3.4.4 Cost Estimations of 2020/2030 scenario

The prices for the HV DC transmission lines and the conversion stations are assumed to remain the same regarding the length of the lines and costs per station (Table 62). However, with the increase of the capacity of one line from 5 GW to 6.5 GW this finally accounts to a reduction of the investment costs of 30%. This reduction is also considered for the AC lines leading to investment costs of 140 million € per GW for each 1,000 km. Operation and maintenance costs, progress ratio as well as lifetime are unchanged to the values of today.

Table 62. Assumptions for cost estimations for 2020/2030 transportation systems.

|                                |                                                                                                                                                                                                                                             |
|--------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Transmission HVDC Lines</b> | Investment costs: 300 million €/1000 km (6.5 GW) (30 % reduction)<br>HVDC-Station: 2 x 350 million € (6.5 GW)<br>Lifetime: 25 years<br>O&M costs: 1 % p.a. of investment costs<br>Progress ratio: 0.96 (starting at 10,000 km as reference) |
| <b>Transmission HVAC Lines</b> | Investment costs: 140 million €/1000 km/GW (30 % reduction)<br>Lifetime: 25 years<br>O&M costs: 1 % p.a. of investment costs<br>Progress ratio: 0.96 (starting at 10,000 GW km as reference)                                                |

Explicit amounts of the costs of a AC/DC conversion station as well as the price per 1,000 km DC transmission line is listed in Table 63 for several total DC line lengths within this scenario.

Table 63. Assumptions for investment costs for several lengths of HV DC transmission lines in 2020/2030.

| Installation within Scenario | Costs per 1,000 km | Costs per HVDC-Station |
|------------------------------|--------------------|------------------------|
| <10,000 km                   | 0.300 billion €    | 0.700 billion €        |
| 20,500 km                    | 0.288 billion €    | 0.671 billion €        |
| 91,300 km                    | 0.263 billion €    | 0.615 billion €        |
| 102,500 km                   | 0.262 billion €    | 0.610 billion €        |
| 142,300 km                   | 0.257 billion €    | 0.599 billion €        |
| 162,000 km                   | 0.255 billion €    | 0.594 billion €        |
| 205,200 km                   | 0.251 billion €    | 0.586 billion €        |
| 307,800 km                   | 0.245 billion €    | 0.572 billion €        |

#### 4.1.3.4.5 Estimation of total transportation distances

The electricity generated in the zones A1 to A3 is primarily passed through the storage systems before sent to the supply zone. Conducing of the electricity over the short distance from generation to the storage plants is done with AC lines. From storage it is sent in the first instance via DC transmission lines to the center of the next adjacent supply zone. From there the electricity is further distributed to the other zones.

For transmission of the electricity to the supply zone, the three paths T1 to T3 of Figure 40 were chosen, connecting each generation zone with a separate line to the supply zone, trying to minimize an expensive crossing and way through the sea. Generation zone A1 thus is connected to Madrid, Spain, zone A2 to Rome, Italy, and zone A3 through Greece to Skopje in Macedonia (see Table 64, including the corresponding distances). The generation zone A1b is connected to the start point of the T1 transmission line at Tanger, Morocco. Whereas a line between Morocco and Spain yet exists, the T2 and T3 lines (as well as T1b) are still to be built.

Table 64. Distance to the next supply zone for each generation region in North Africa.

| Zone Z | Reference supply point | Average distance to reference point |
|--------|------------------------|-------------------------------------|
| A1     | Madrid (Spain)         | 1,300 km                            |
| A1b    | Tanger (Morocco)       | 2,000 km                            |
| A2     | Rome (Italy)           | 2,600 km                            |
| A3     | Skopje (Macedonia)     | 3,800 km                            |

Furthermore, as high power levels of electricity have to be passed through to the northern supply countries, the exchange of electricity between the neighbouring supply zones is estimated to be done also by high voltage DC lines whereas the distribution within one zone is done via the yet existing AC net. Therefore, the distances among the individual supply zones were estimated and listed as a matrix in Table 65, including the distances to the generation zones. The distances were determined between the reference cities near the centre of each zone, connecting neighbouring zones by a direct, straight line though minimizing expensive distances for crossing the sea.



Table 65. Estimations for Average Transmission Distances between Different Supply Zones.

| Z  | Reference City | B    | D    | E    | F    | G    | I    | N    | P    | S    | U    |
|----|----------------|------|------|------|------|------|------|------|------|------|------|
| B  | Brussels       |      | 400  | 1600 | 700  | 2100 | 1400 | 1100 | 1100 | 800  | 600  |
| D  | Frankfurt      | 400  |      | 1800 | 700  | 1700 | 1200 | 1000 | 800  | 500  | 1000 |
| E  | Madrid         | 1600 | 1800 |      | 1200 | 3000 | 1900 | 2700 | 2400 | 1900 | 2100 |
| F  | Lyon           | 700  | 700  | 1200 |      | 1800 | 900  | 1700 | 1200 | 700  | 1200 |
| G  | Skopje         | 2100 | 1700 | 3000 | 1800 |      | 800  | 2300 | 1000 | 1400 | 2700 |
| I  | Rome           | 1400 | 1200 | 1900 | 900  | 800  |      | 2100 | 1100 | 700  | 2000 |
| N  | Gothenburg     | 1100 | 1000 | 2700 | 1700 | 2300 | 2100 |      | 1300 | 1300 | 1700 |
| P  | Bratislava     | 1100 | 800  | 2400 | 1200 | 1000 | 1100 | 1300 |      | 500  | 1800 |
| S  | Insbruck       | 800  | 500  | 1900 | 700  | 1400 | 700  | 1300 | 500  |      | 1500 |
| U  | Manchester     | 600  | 1000 | 2100 | 1200 | 2700 | 2000 | 1700 | 1800 | 1500 |      |
| A1 | NA West        | 2900 | 3100 | 1300 | 2500 | 4300 | 3200 | 4000 | 3700 | 3200 | 3400 |
| A2 | NA Center      | 4000 | 3800 | 4500 | 3500 | 3400 | 2600 | 4700 | 3700 | 3300 | 4600 |
| A3 | NA East        | 5900 | 5500 | 6800 | 5600 | 3800 | 4600 | 6100 | 4800 | 5200 | 6500 |

In Table 66 for the countries of each supply zone the best-suited generation zone including its total distance is listed.

For the base load scenario, the total lengths of the transmission lines from generation to every of the supply zones, including the different power levels needed by the individual zones, were calculated manually for the distribution of the whole demand among all of the supply zones along their individual demand as presented in Table 33 and Table 34. For simplification, the obtained experience values were used for the peak load scenarios: the total length of the HV DC lines was plotted over the corresponding complete power level (Figure 49). The total length here is obtained by multiplying the length of the transmission distance with the number of necessary transmission lines, accounting for a maximal power capacity of the transmission lines of 5 GW today and 6.5 GW in the future (see paragraphs 4.1.3.4.1 and 4.1.3.4.2).

Table 66. Connection of Supply Zones with Generation Zones in North Africa.

| Zone | Countries                                  | Supply Zone    | Transmission Distance |
|------|--------------------------------------------|----------------|-----------------------|
| B    | Belgium, Netherlands, Luxembourg           | A1 (NA West)   | 2,900 km              |
| D    | Germany                                    | A1 (NA West)   | 3,100 km              |
| E    | Spain, Portugal                            | A1 (NA West)   | 1,300 km              |
| F    | France                                     | A1 (NA West)   | 2,500 km              |
| G    | Greece, FR Yugoslavia, Macedonia, Croatia  | A3 (NA East)   | 3,800 km              |
| I    | Italy                                      | A2 (NA Center) | 2,600 km              |
| N    | Denmark, Norway, Sweden, Finland (Iceland) | A1 (NA West)   | 4,000 km              |
| P    | Poland, Czech and Slovak Republic, Hungary | A2 (NA Center) | 3,700 km              |
| S    | Switzerland, Austria, Slovenia             | A2 (NA Center) | 3,300 km              |
| U    | Untied Kingdom, Ireland                    | A1 (NA West)   | 3,400 km              |

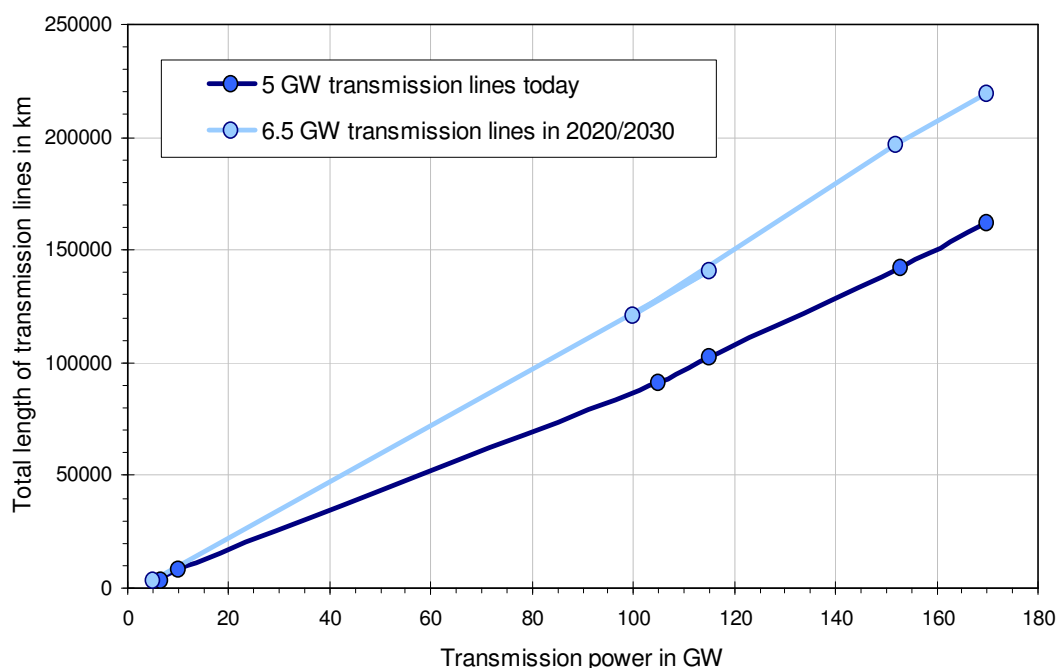


Figure 49 Total lengths of transmission lines in dependence on the transmission power, calculated for zone A3 at the base load scenarios

The dependence of the total length of the transmission lines on the corresponding power level in Figure 49 shows an approximately linear coherency. Therefore, at the remaining load and the combined scenarios, the length of the transmission lines has not been calculated manually and in detail for each power level, but the following simplified assumptions have been made for calculation of the total line length and the number of necessary conversion stations in dependence on the transmission power level:

Today's scenarios (5 GW lines):

- 1,300 km/GW, accounting for: line length / supply zone power demand
- 0.23 HVDC stations per GW total power demand
- 18% total transmission losses

2020/2030 scenarios (6.5 GW lines):

- 950 km/GW, accounting for: line length / supply zone power demand
- 0.17 HVDC stations per GW total power demand
- 14% total transmission losses

Here, the first factor shows the coefficient of the total line length in dependence on the demand power level for the whole supply zone, the second factor multiplied with the supply demand power level and rounded up to the next pair integer yields the number of necessary stations and the last number tells the amount of total transmission losses. The latter one sums up to 18% for the state of the art transmission lines and to 14% for 2020/2030.

#### 4.1.4 Economic Calculations

As the aim of this study has been as a matter of principal the comparison of several different scenarios and not a detailed cost analysis of a concrete project, the economic calculations have been kept as simple as possible. The following expressions and equations have been used:

- **Annuity:**  $a = \frac{ir}{(1 - (1 + ir)^{-n})}$   
 with  $ir$  : discount rate (6 and 8% assumed)  
 $n$  : system lifetime in years

The Annuity is the amount of annual payback to amortize the debts by the end of the system lifetime. The annuity is a fix amount remaining constant over the years and includes the redemption quota and interest amount within the discount rate.

- **Present Value:**  $PV = c_{Inv} + c_{O\&M} \cdot \frac{(1 + ir)^n - 1}{ir \cdot (1 + ir)^n}$   
 with  $c_{Inv}$  : investment costs  
 $c_{O\&M}$  : annual operation and maintenance costs

The Present Value is a symbolic value used to make different investments or projects with different financing plans comparable. It describes the imaginary value of a project or the amount of an investment, which you have to pay at project start (in the present), to come to the same result at the end of the project lifetime. The PV is composed of the real investment costs  $c_{Inv}$  and the annually pending costs for operation and maintenance  $c_{O\&M}$  calculated down to the project start at present. For simplicity, investment costs have been accounted here only as one amount to be paid yet at the project start.

- **Levelised Electricity generation Costs:**  $LEC = \frac{PV \cdot a}{E_a}$   
 with  $E_a$  : annual demand

The Levelised Electricity Costs are the finally resulting costs, which arise for the production of a certain amount of electricity, usually stated as Cents per kWh. It is calculated here simplified by accounting the Present Value multiplied with the Annuity, giving the annual expenses, and dividing this by the annual yield of electricity (which has to be the demand as losses have to be respected).

The reference currency is Euro and as reference year the year 2000 has been considered. Furthermore, accounting for expectable land prices in the range of less than a few €/m<sup>2</sup> in the desert and comparing them with the costs of one square meter of photovoltaic or mirror area, it can be stated that the costs for the ground does not show a significant contribution. Therefore, land prices have been neglected where not yet included in the given costs.

#### 4.1.5 Performance of the simulation runs

For a detailed dynamic simulation and analysis of power plants run by renewable energies, the software tool “greenius” (see Figure 50) was developed within DLR [Gre]. It includes the technical and economical modulation of photovoltaic, solar thermal power plants and wind energy. This tool has been used for modelling of the generation part (including storage for solar thermal) of the scenario. Besides the technical data presented above, further input data for the simulation runs are hourly weather data like e.g. direct normal, global horizontal and diffuse horizontal irradiation data. These data has been taken at 5 sites within each generation zone from either the S@tellite or (where no

S@tellight data available) from the Meteonorm database in hourly resolution (see Figure 51 for the sources and Table 30 to get the information which source was used at which location). Furthermore, a demand load curve can be given which then has to be covered by the plant output.

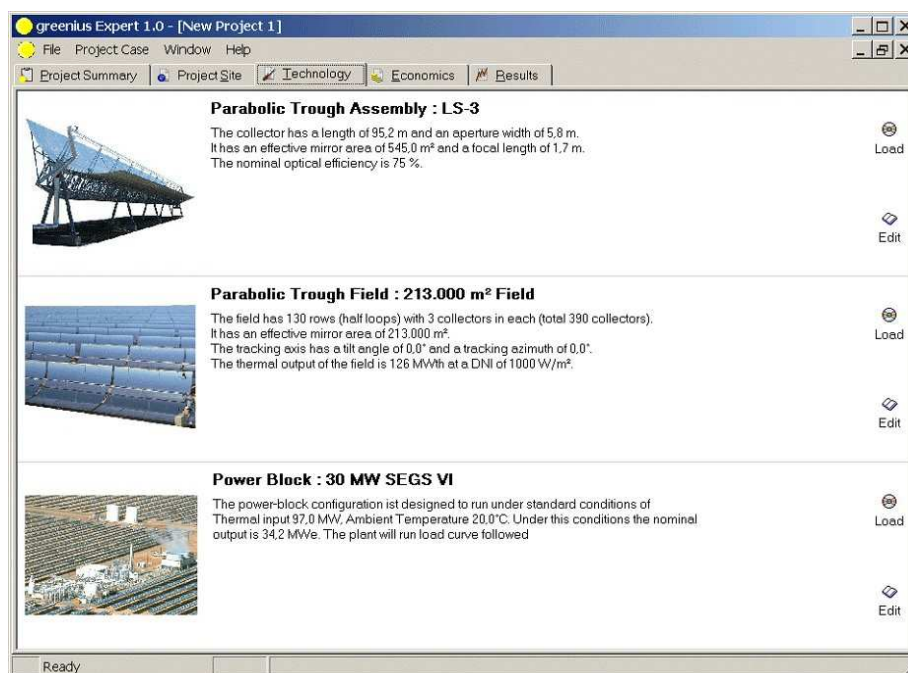


Figure 50. greenius software tool for modelling of power plants for renewable energies

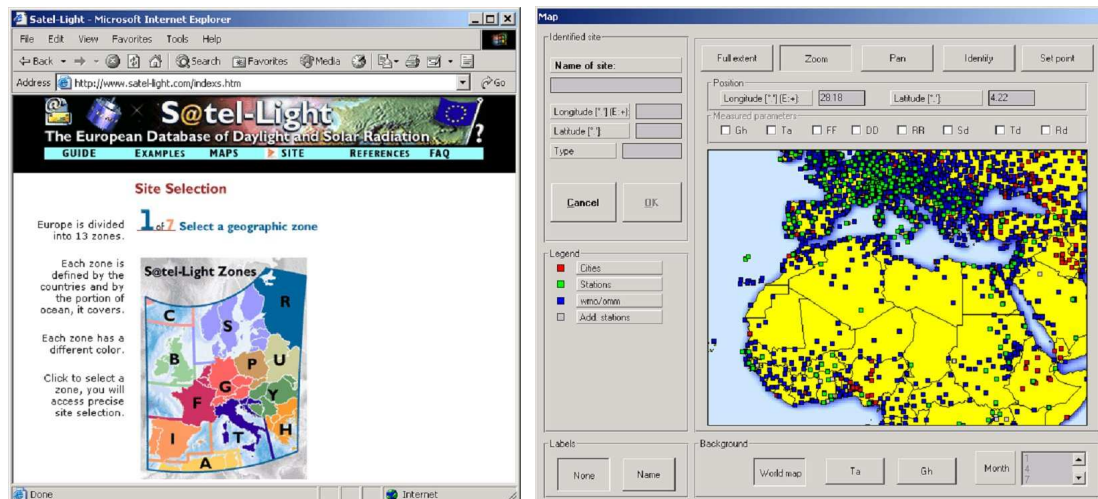


Figure 51. Sources for irradiation data: S@tellight (left) and Meteonorm (right)

The calculations have been performed with greenius for photovoltaic and solar thermal power plants for each of the 5 sites within each generation zone. Afterwards, the hourly output power of the single sites within one generation zone have been mixed to yield an average power generation of several solar power plants equally distributed over the whole generation zone. The solar thermal power plant scenarios were simulated in plant units of 100 MW, which is a practical plant dimension. Larger plant sizes would lead to higher specific costs because heat losses would increase due to long distances. For higher power levels the results of the 100 MW plants have been scaled up accounting for parallel

installation of several 100 MW plants. Photovoltaic plants were scaled up in analogous way from units of 1 GW<sub>p</sub>.

The set up of the scenario combining the scale up of the generation plants, the storage system and the transmission lines was subsequently done afterwards also for hourly resolution. Here the economic calculations were included, yielding detailed costs for the individual components as well as the resulting levelised electricity costs. Optimization of generation plant size and location, storage size, etc. has been done with the aim of minimizing the LEC. The storage capacity has been dimensioned that way that it will not run short within the whole year. As results, the necessary capacities of the generation system, the storage, the transmission lines as well as the costs and cost splitting is presented for the announced power levels in detail in the following paragraphs.

## **4.2 Provision of Base-Load**

In the first package the provision of base load by solar power plants (photovoltaic and solar thermal) has been examined. Therefore, the generation process, the amount of its total output has been analyzed as well as its hourly course for both of the generation systems and thus optimal configurations derived. Finally, the calculations of several power levels from 0.5 GW to 150 GW have been done for the optimized systems within the three generation zones. The summarizing results will be presented as well as several analysis steps.

### ***4.2.1 Analysis and optimization of photovoltaic power supply***

In contrary to solar thermal power plants, which use only the direct solar irradiation, photovoltaic panels use global irradiation composed from the direct solar and the diffuse irradiation from sky. Whereas solar thermal must be tracked to the solar path, photovoltaic panels need not. Mounting the panels is far cheaper then and the higher income of a tracked PV usually does not compensate the higher costs of the tracking system. However, the orientation of the panel is important for the annual gain and the daily and monthly variation. Optimization is the scope of the next paragraph.

#### ***4.2.1.1 Influence of Tilt Angle Variations on Daily Output***

As announced above, the orientation of the photovoltaic panels shows high influence on the variations and the daily and hourly course of the generated electricity. Figure 52 shows the course of the daily sums of photovoltaic panels for three different inclination angles as calculated for the Kenitra location in Morocco.

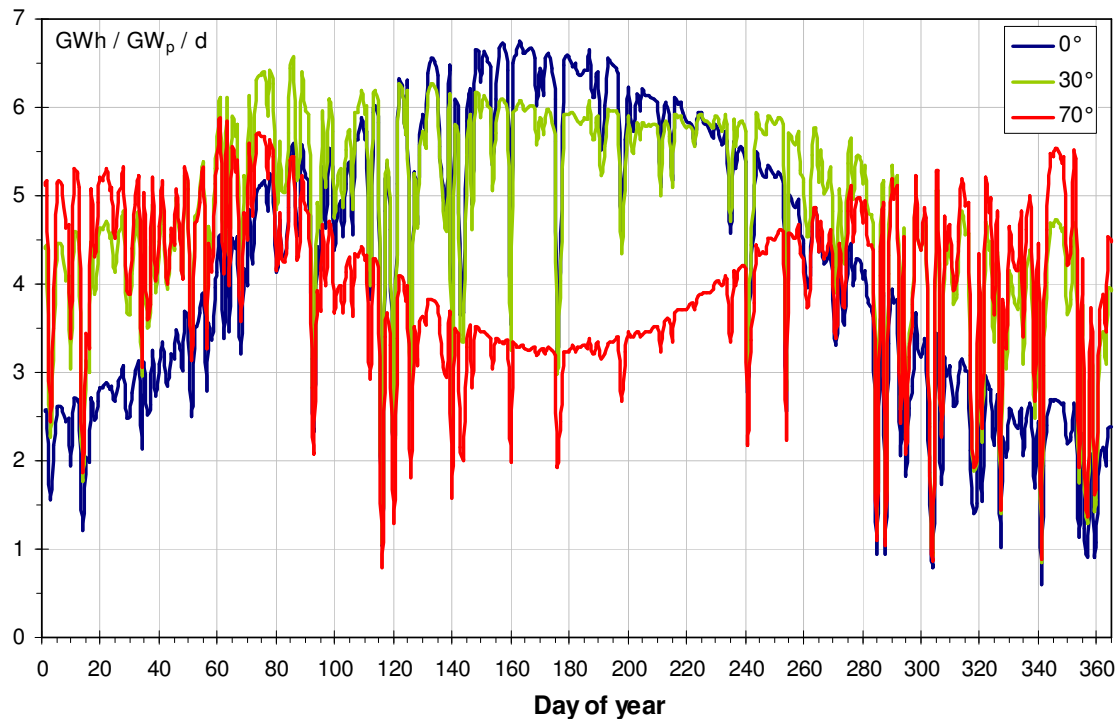


Figure 52. Daily output of photovoltaic installations at Kenitra (Morocco) with a global irradiation of 2,009 kWh/(m<sup>2</sup>a) in Zone A1, depending on angle of inclination

The inclination angle names the inclination of the panel to a horizontal surface to an axis oriented to the south, e.g. 0° inclination means a horizontally mounted panel. The daily course of the three inclination angles shows considerable different characteristic: A flat mounted panel (0° inclination) shows daily sums in the winter in the order of about 2.5 GWh per installed GW<sub>p</sub> and per day. Towards the summer, when the maximal sun position gets higher at that location, daily sums of 6.5 GWh/GW<sub>p</sub>/d are reached. This means a high variation during the year, what does not fit the constant base load demand throughout the year. Inclining the panels 70° to the south increases the power output in winter considerably but reducing generation in summer, also lowering the total annual generation. With an inclination angle of 30° the energy gain during winter decreases only slightly with a significantly higher gain in the summer months compared to the 70° inclined panels. The exceeding generation during summer could be sold at different conditions.

Comparing the curves of Morocco in Figure 52 to those in Figure 53 for the Aswan site in Egypt, the latter ones show fairly smooth lines whereas the daily generation in Morocco shows clear breakdowns in the range of few days. These breakdowns in daily generation are due to bad weather conditions. Vice versa, this shows for the Egyptian location perfect conditions for solar power generation due to the low probability of a cloudy period.

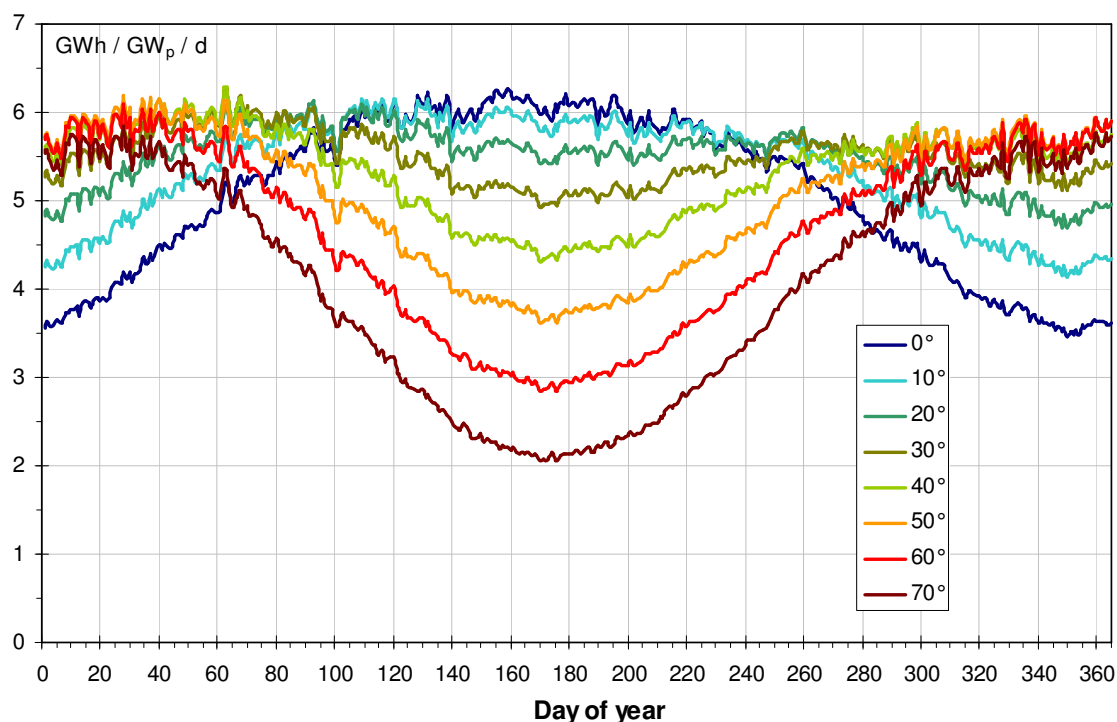


Figure 53. Daily output of photovoltaic installations at Aswan (Egypt) with a global irradiation of 2,466 kWh/(m<sup>2</sup>a) in Zone A3, depending on angle of inclination.

Furthermore, the daily output of panels with different inclination angles in Figure 53 shows a similar characteristic for Aswan as for Morocco: high output in summer and low in winter for low inclination angles and vice versa for high inclination angles. Therefore, as within the operation and maintenance process the panels have to be checked and cleaned regularly, there exists the possibility to change the inclination angle of the panels at some day at the beginning of spring to 10° for the summer months and some day at the beginning in autumn to 60° for the winter months. Thus the annual generation sum could be maximized. The mounting device of the panels was assumed to be constructed in that way that the change can be done easily e.g. beside the cleaning process. Costs of the mounting device were assumed to be 2% higher than those for a fixed device. The change of the inclination angle shows no need for an exact date.

#### 4.2.1.2 Simulation Results for PV Generation in Zone A1

Figure 54 shows in how much hours within one year the plotted percentage of the nominal peak power production is reached. The graph represents the average of all locations of generation zone A1. A full power production at the nominal peak power level of 100% is never reached within the whole year, but values between 85 and 90% for only 20 hours within one year. A power output of more than 50% of the nominal power will be available within slightly beyond 2000 h/a. Over all, the PV plant produces electric power within no more than 4470 h/a.

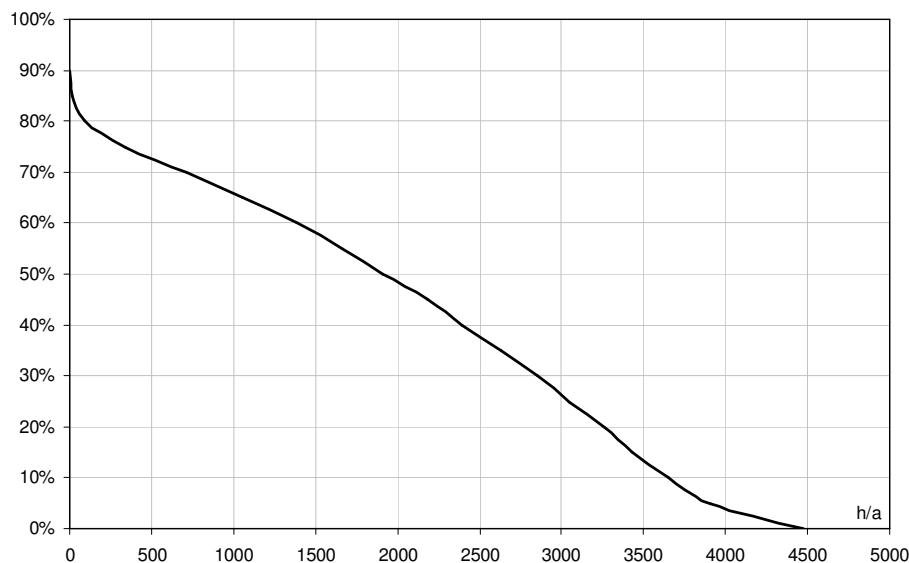


Figure 54. Percentage of Nominal Power Production with obtained full load hours for state-of-the-art PV systems in Generation Zone A1 obtained by hourly simulation

The monthly sums of generated energy in zone A1 is presented in Figure 55. Due to a fix inclination angle of  $30^\circ$ , which was chosen here, the monthly sums in summer are with over  $160 \text{ GWh/GW}_p$  slightly higher than for the winter months with between 120 to  $140 \text{ GWh/GW}_p$ . March shows the highest monthly value with nearly  $180 \text{ GWh/GW}_p$ .

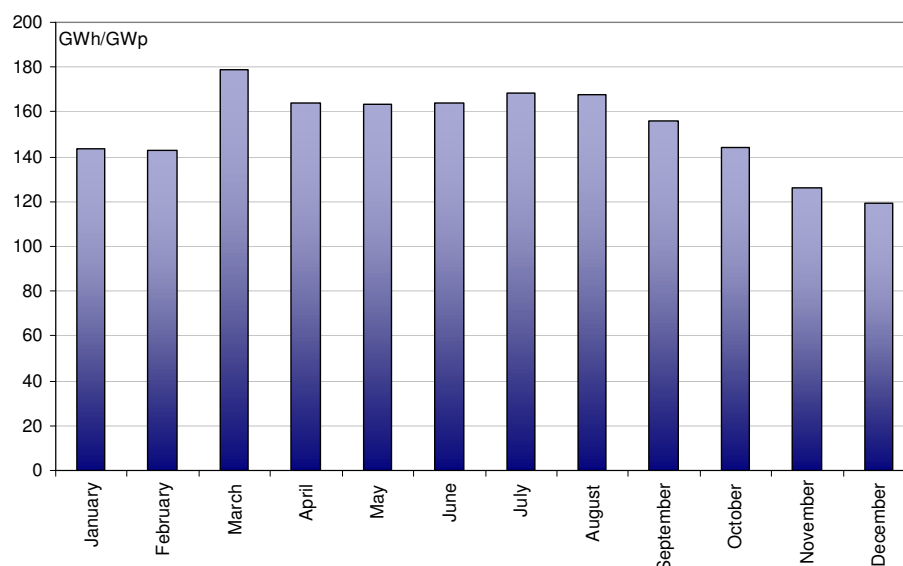


Figure 55. Monthly Generation of state-of-the-art PV systems in Generation Zone A1 obtained by hourly simulation at a chosen inclination angle of  $30^\circ$

#### 4.2.1.3 Simulation Results for PV Generation in Zone A2

In Zone A2 the maximal reached power is lower than in zone A1 (Figure 56). Power generation between 80 and 85% of the nominal peak power is achieved for only 29 hours per year. Equally to



zone A1, a power output higher than 50% of the nominal power is available within 2000 h/a, too. However at very low power levels beyond 5% of the nominal peak power, electricity is delivered here within up to 4800 h/a and therefore 300 hours longer than in Zone A1.

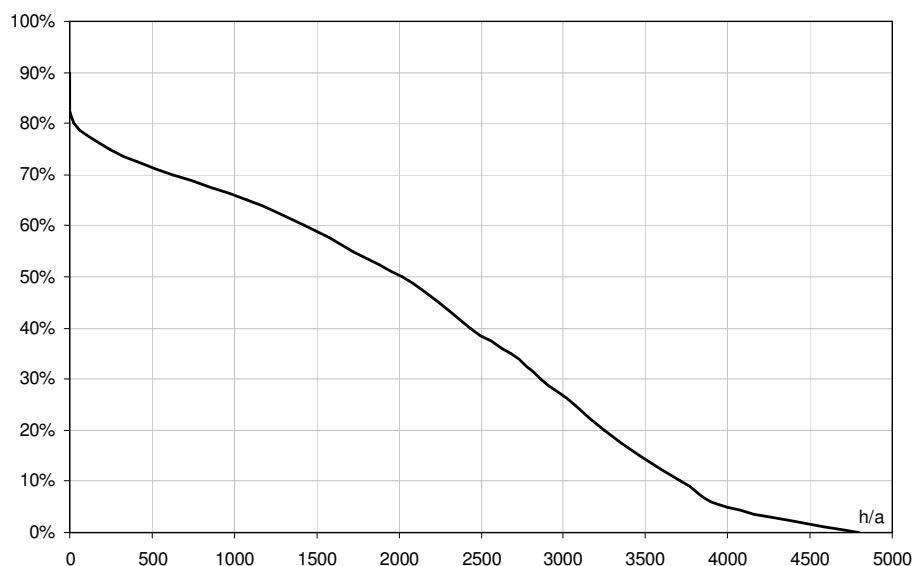


Figure 56. Percentage of Nominal Power Production with obtained full load hours for state-of-the-art PV systems in Generation Zone A2 obtained by hourly simulation

The monthly sums of generated energy in zone A2 are varying within a smaller range than those in zone A1: They have values between 140 and 170 GWh/GW<sub>p</sub> (Figure 57), which in addition hardly show that characteristic of higher values in summer and lower values in winter but account with their highest values in August and March/April to the perpendicular incident angle of the solar irradiation onto the 30° inclined panels in this months.

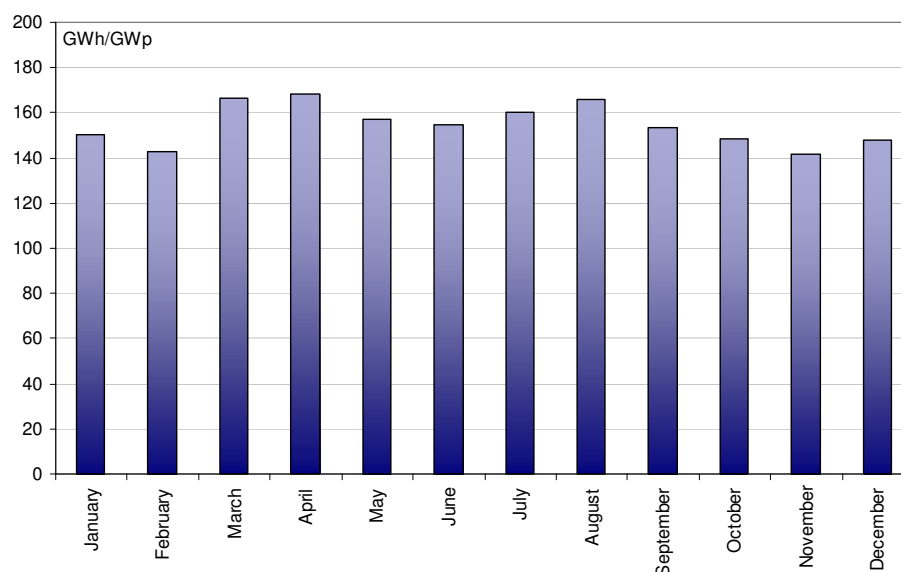


Figure 57. Monthly Generation of state-of-the-art PV systems in Generation Zone A2 obtained by hourly simulation

#### 4.2.1.4 Simulation Results for PV Generation in Zone A3

In zone A3 higher power levels (accounting to higher percentages) are reached as compared to the same number of working hours per year within the other generation zones. Hence, the power output of 50% is available within 2185 hours per year. Highest gains between 85 and 90% however are also reached only within 11 hours and over all no more than 4233 hours per year the plant is working and delivering electricity, which is less than in zones A1 and A2.

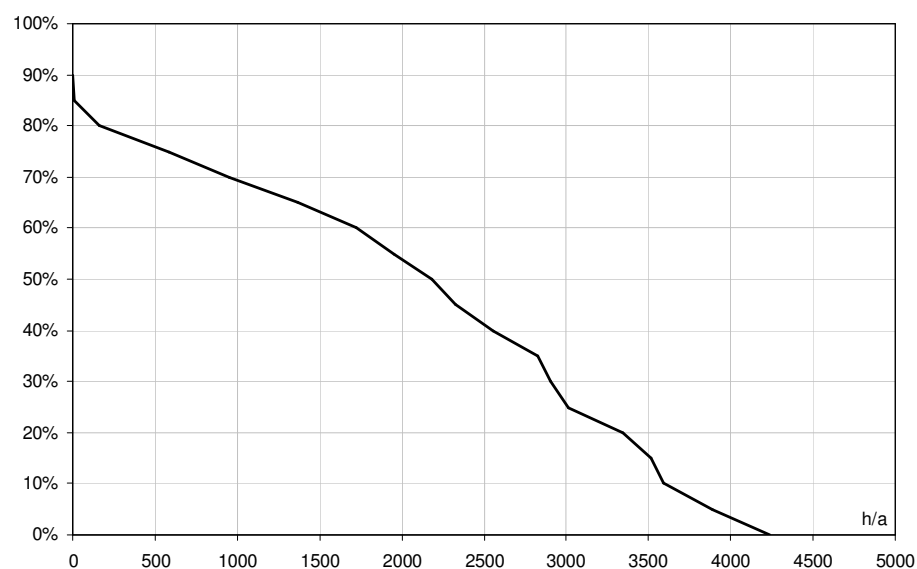


Figure 58. Percentage of Nominal Power Production with obtained full load hours for state-of-the-art PV systems in Generation Zone A3 obtained by hourly simulation

Having a look at the monthly sums of generated energy in zone A3, it can be seen that the highest values occur in March and October. Here, due to the chosen inclination angle of  $30^\circ$ , the solar irradiation is perpendicular to the panels. Its monthly sums are with between 150 and 180 GWh/GW<sub>p</sub>, again higher as in the latter zones A2 and A1 and do not show a strong variation within different seasons.

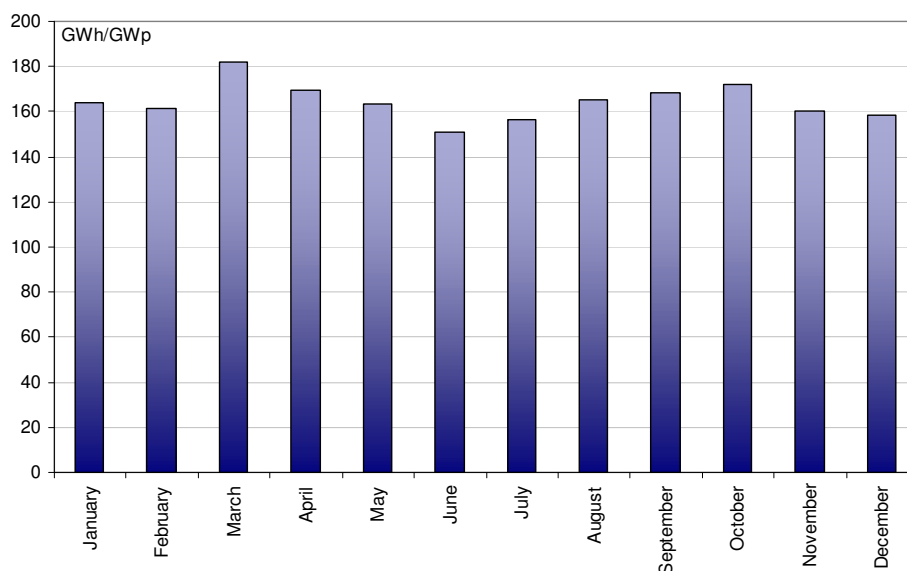


Figure 59. Monthly Generation of state-of-the-art PV systems in Generation Zone A3 obtained by hourly simulation

## 4.2.2 Solar Thermal Systems

The solar thermal troughs are only collecting direct solar irradiance and must hence be tracking the sun. Principally, there are two possibilities of mounting the troughs: along an axis directing from north to south, following the sun's path along the azimuth, or mounted along an axis in east-west direction, the collector following the sun's height angle. The highest annual gain is received with a north-south configuration. However, the energy gain yields far lower values in the winter months due to lower sun height angles than in the summer months, thus showing a strong variation of in the course of the year. Mounted in east-west direction, the annual gain is considerably lower but the need for expensive seasonal storage can be avoided like this. Thus, this alignment has been chosen for the solar thermal scenarios.

### 4.2.2.1 Simulation Results for ST Generation in Zone A1

Figure 60 shows in analogous manner to Figure 55 the monthly sums per gross nominal electric power of the power plant as average of the locations within generation zone A1. The calculations have been done here for a plant with a collector field size of 1.8 million square meters, a nominal gross power of the steam turbine of 100 MW<sub>el</sub> and an included thermal storage with a capacity of 18 h. The monthly sums are varying within a broad range, showing low values of around 400 GWh/GW<sub>el, gross</sub> in the months from September to December and considerably higher values of around 550 GWh/GW<sub>el</sub> in June and July, but also in March and January.

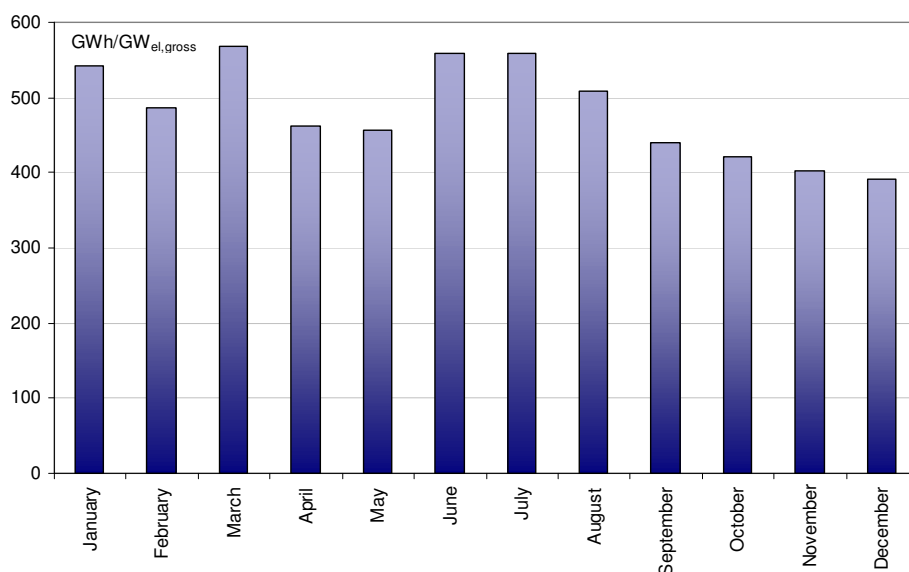


Figure 60. Monthly Generation of state-of-the-art Solar Thermal Power Plants in Generation Zone A1 obtained by hourly simulation (1.8 million m<sup>2</sup> collector field per 100 MW<sub>el</sub>, 18 h thermal storage)

The corresponding plot analogous to Figure 54, showing the number of hours in which a certain percentage of the nominal electric gross power output is exceeded, is presented in Figure 61 for the same power plant as above with a 18 h thermal storage. For the solar thermal power plants, the nominal power is nearly reached with only small losses of some parasitics, etc., within nearly 3,000 hours per year. At higher numbers of hours per year the used capacity is decreasing in several steps. Over all, the solar power plant as configured like this is delivering power for at least 8,200 hours per year and hence at a significantly higher period within one year as photovoltaic delivers electricity. This is due to the storage included in the solar thermal power plant, which allows the production of energy still after sunset. The stepwise decrease is due to the fact that the calculations were performed at only five sites hence yielding 5 steps. Within the first step until the 3,000 hours all plants at the five sites were producing electricity, within the next step from 3,000 to 5,000 h/a only four plants contributed to power production. In reality with a bigger amount of plants at different locations, the curve would decrease more smoothly with smaller or even without remarkable steps.

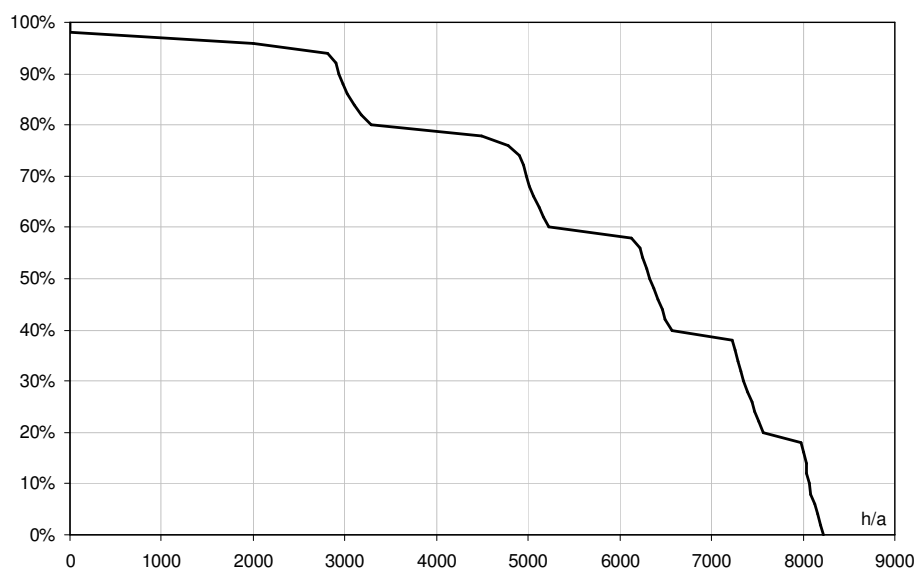


Figure 61. Percentage of Nominal Power Production with obtained full load hours for state-of-the-art Solar Thermal Power Plants with 18 h thermal storage in Generation Zone A1 obtained by hourly simulation

However, by enlarging the storage capacity and thus also the collector field size, the working of capacity and the output of the power plant can be increased. With storage capacities of 24 hours and a corresponding collector size of 2.37 million square meters, the monthly produced energy is increased and the monthly variation reduced (Figure 62).

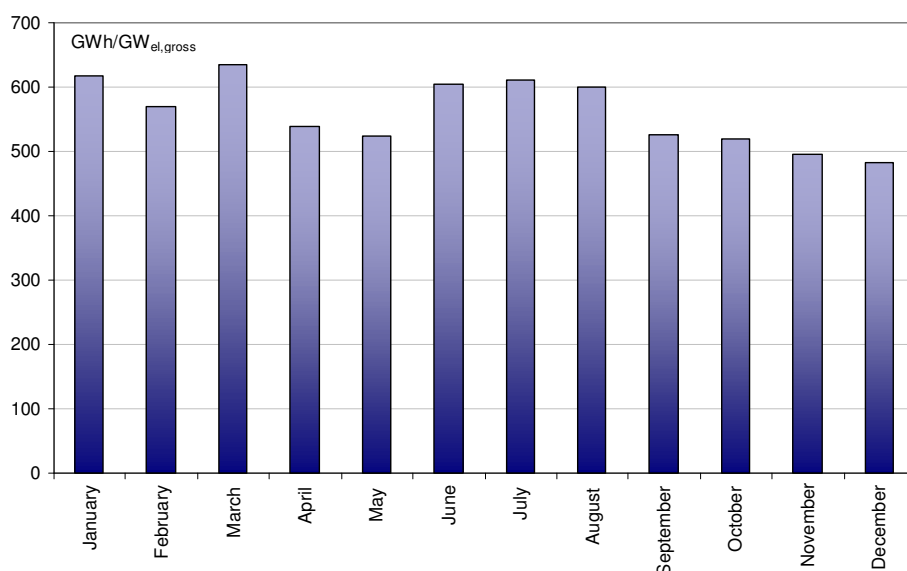


Figure 62. Monthly Generation of state-of-the-art Solar Thermal Power Plants in Generation Zone A1 obtained by hourly simulation (2.37 million m<sup>2</sup> collector field per 100 MW<sub>el</sub>, 24 h thermal storage)

The increase of the number of working hours per year can also be noticed in the plot in Figure 63. Now, with the higher capacities the plant is working nearly within the whole 8,760 hours per year, delivering 6630 GWh/GW<sub>el,gross</sub> as yearly sum.

Finally, with the variation of the storage capacity and the corresponding collector size it could be shown that this configuration with the storage capacity of 24 hours and 2.37 million square meters is an optimal configuration, which then also has been used for further calculations.

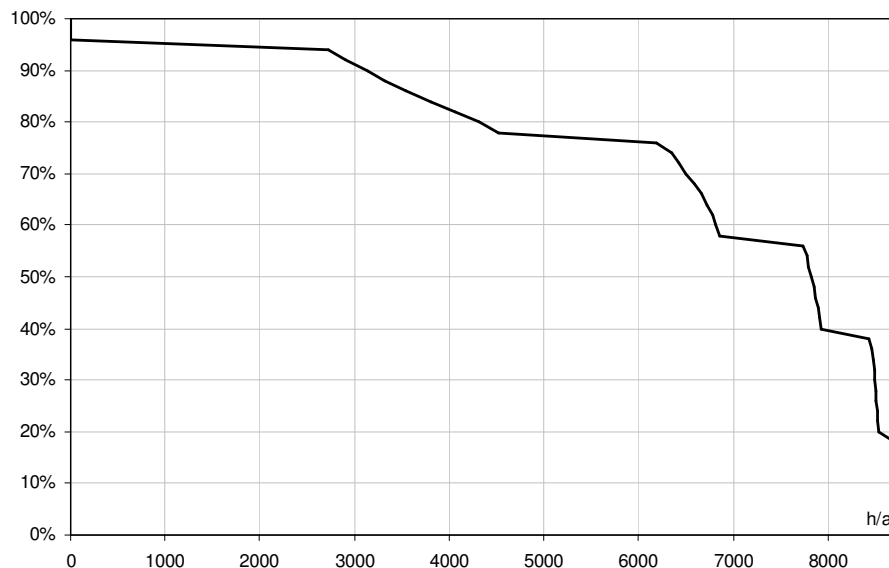


Figure 63. Percentage of Nominal Power Production with obtained full load hours for state-of-the-art Solar Thermal Power Plants with 24 h thermal storage in Generation Zone A1 obtained by hourly simulation

#### 4.2.2.2 Simulation Results for ST Generation in Zone A2

At zone A2 the calculations were also performed for 24 h storage and a collector field size of 2.37 million m<sup>2</sup>. The monthly sums are about in the same range as in zone A1 between 490 and 630 GWh/GW<sub>el,gross</sub> with higher values in summer as well as December and January (see Figure 64). The annual sum accounts to 6910 GWh/GW<sub>el,gross</sub> and thus 4% higher than in zone A1.

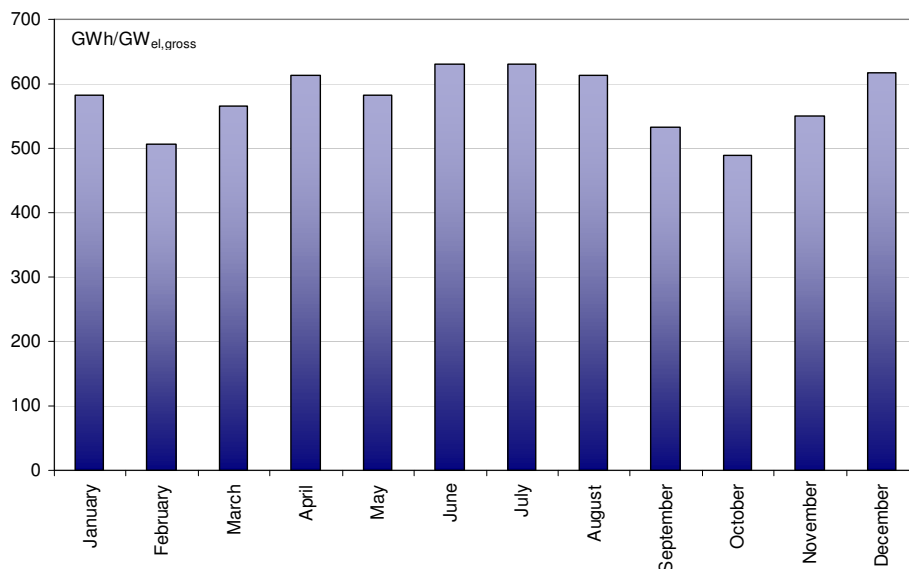


Figure 64. Monthly Generation of state-of-the-art Solar Thermal Power Plants in Generation Zone A2 obtained by hourly simulation (2.37 million m<sup>2</sup> collector field per 100 MW<sub>el</sub>, 24 h thermal storage)

The number of working hours of the solar thermal power plants in zone A2 are slightly higher than in zone A1 and very similar. Now within all the 8,760 h of one year energy is generated. As in zone A1 here the five steps due to the calculation at five sites can be found in Figure 65 with the last step at the full 8,760 hours and the forecast short before.

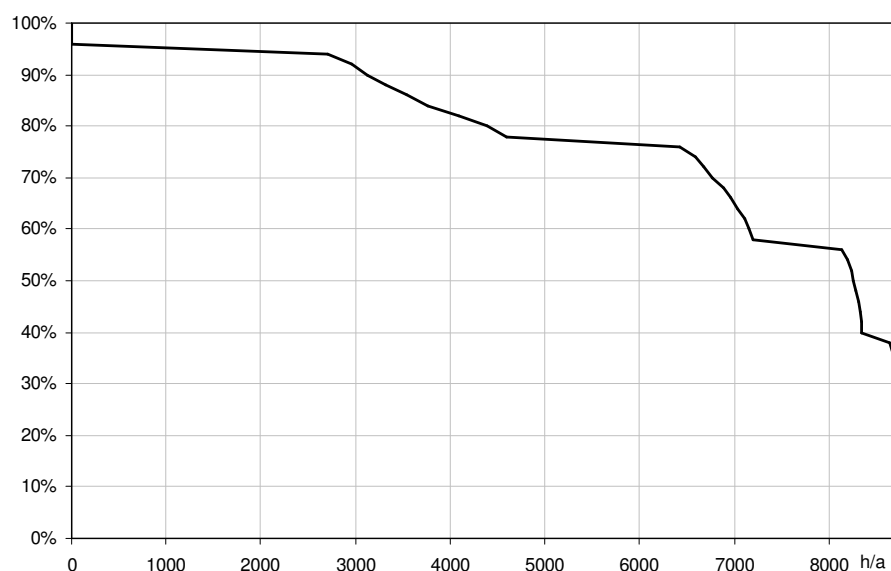


Figure 65. Percentage of Nominal Power Production with obtained full load hours for state-of-the-art Solar Thermal Power Plants with 24 h thermal storage in Generation Zone A2 obtained by hourly simulation

### 4.2.2.3 Simulation Results for ST Generation in Zone A3

The monthly sums of generated electricity in zone A3 show in contrary to zones A1 and A2 a considerable lower variation with values between 613 and 685 GWh/GW<sub>el,gross</sub> (Figure 66). The annual sum accounts to 7982 GWh/GW<sub>el,gross</sub>. No variation due to seasons can be noticed.

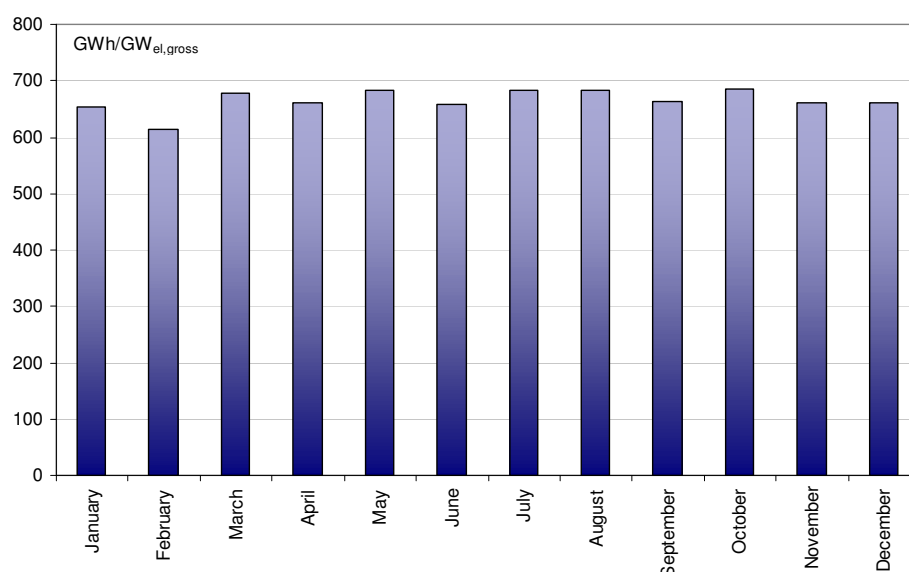


Figure 66. Monthly Generation of state-of-the-art Solar Thermal Power Plants in Generation Zone A3 obtained by hourly simulation (2.37 million m<sup>2</sup> collector field per 100 MW<sub>el</sub>, 24 h thermal storage)

This low variation of monthly values can clearly be seen in Figure 67, where the percentage of the nominal output is plotted over its working hours: here electricity is generated to an amount of about 95% of its nominal electric gross power for about 6,000 hours per year, then only decreasing to a value of 75% at the full annual running time. No steps can be noticed at the decrease. This is due to the fact that in zone A3 there are only few and short cloudy periods. Lacking irradiation can nearly be covered by storage with a capacity of 24 h.



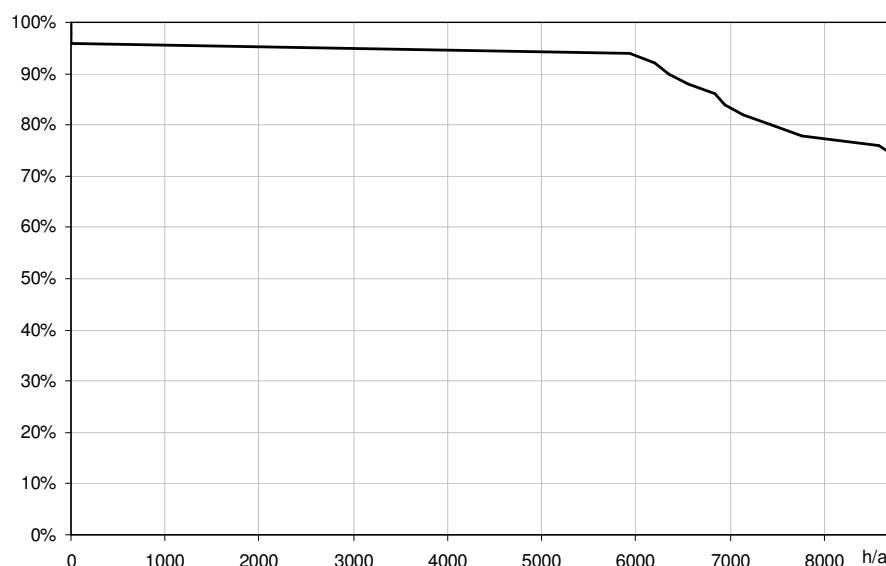


Figure 67. Percentage of Nominal Power Production with obtained full load hours for state-of-the-art Solar Thermal Power Plants with 24 h thermal storage in Generation Zone A3 obtained by hourly simulation

#### 4.2.3 Summary of Results for Base-Load Scenarios of today

After the optimization of the configuration of the power generation plants, simulations of the scenarios were done for five different power levels for photovoltaic and solar thermal power plants. The most important assumptions like the selected generation zone and installed capacities are presented in Table 67 for PV and Table 68 for solar thermal for a state-of-the-art base load power supply.

Table 67. Calculations of base load supply for PV systems today

| Demand                         | GW              | 0.5    | 5      | 10     | 100    | 150    |
|--------------------------------|-----------------|--------|--------|--------|--------|--------|
| <b>Assumptions</b>             |                 |        |        |        |        |        |
| Generation zone                |                 | A1     | A1     | A3     | A3     | A3     |
| PV Capacity                    | GW <sub>p</sub> | 3      | 33     | 65     | 653    | 997    |
| Pumped hydro                   | GW              | 2.1    | 23.65  | 42.51  | 424.77 | 651.10 |
| Storage Capacity               | GWh             | 180    | 820    | 200    | 3,000  | 3,500  |
| <b>Resulting LEC</b>           |                 |        |        |        |        |        |
| Interest rate 6 %              | €/kWh           | 0.284  | 0.207  | 0.180  | 0.146  | 0.142  |
| Interest rate 8 %              | €/kWh           | 0.332  | 0.243  | 0.209  | 0.170  | 0,165  |
| <b>LEC Breakdown for IR=6%</b> |                 |        |        |        |        |        |
| PV generation                  |                 | 58.1 % | 52.0 % | 51.4 % | 48.1 % | 46.8 % |
| Transmission                   |                 | 5.5 %  | 8.3 %  | 13.3 % | 11.6 % | 15.0 % |
| Storage and dumping            |                 | 36.4 % | 39.7 % | 35.3 % | 40.2 % | 38.2 % |

Table 68. Calculations for ST systems today

| Demand                         | GW               | 0.5    | 5      | 10     | 100    | 150    |
|--------------------------------|------------------|--------|--------|--------|--------|--------|
| <b>Assumptions</b>             |                  |        |        |        |        |        |
| Generation zone                |                  | A1     | A1     | A1/A1b | A3     | A3     |
| ST Capacity                    | GW <sub>el</sub> | 0.75   | 7.7    | 15.5   | 150.0  | 220.0  |
| Pumped Hydro                   | GW               | 0.5    | 5.0    | 10.0   | 31.8   | 47.4   |
| Storage Capacity               | GWh              | 62     | 620    | 680    | 255    | 370    |
| <b>Resulting LEC</b>           |                  |        |        |        |        |        |
| Interest rate 6 %              | €/kWh            | 0.136  | 0.095  | 0.083  | 0.060  | 0.057  |
| Interest rate 8 %              | €/kWh            | 0.157  | 0.111  | 0.096  | 0.069  | 0.066  |
| <b>LEC Breakdown for IR=6%</b> |                  |        |        |        |        |        |
| ST generation                  |                  | 67.6 % | 64.1 % | 65.9 % | 67.3 % | 65.3 % |
| Transmission                   |                  | 9.6 %  | 7.2 %  | 11.4 % | 20.9 % | 19.6 % |
| Storage and dumping            |                  | 22.8 % | 28.6 % | 22.7 % | 11.8 % | 15.1 % |

The small power levels of 500 MW and 5 GW were calculated for generation zone A1 because the already existing transmission line T1 can be used then. For solar power at the power level of 10 GW the generation zone has to be extended to Mauretania, pertaining to zone A1b, to get a more uniform power generation. Respectively photovoltaic plants, the inclusion of zone A1b was not sufficient for power generation at economic conditions, thus generation zone was shifted to zone A3.

As result, the levelised electricity costs for a power level of 500 MW for PV panels with an interest rate of 6% yield 28 €-Cents per kWh. Therefore, the installation of a capacity of 3 GW<sub>p</sub> of PV cells and 180 GWh of storage is necessary. Coming to the full supply power level of 150 GW, the LEC is decreasing to 14 €-Cents with a PV capacity of 1000 GW<sub>p</sub> and a storage capacity of 3,500 GWh. The change to generation zone A3 can clearly be noticed in the considerable decrease of the necessary storage capacity in the step from 5 to 10 GW.

With solar thermal power plants far lower LECs of 14 to 6 €-Cents can be reached within these scenarios at an interest rate of 6%. To achieve this result, the installed electric power of the turbine has to be within a range of 0.8 to 220 GW<sub>el</sub> depending on the power level of the scenario. Corresponding needed storage capacities between 62 and 370 GWh are far lower at solar thermal power generation because of the high efficient included thermal storage.

Subsequently, the percentage of the LEC caused by an external storage respectively dumping is with 23 to 15% far lower at solar thermal power plants as at photovoltaic where between 35 and 40% of the LEC are necessary for purposes of storage and dumping. Transmission of the electricity to the supply zones requires an amount of about 5 to 20% of the arising costs.

#### 4.2.4 Summary of Results for Base-Load Scenarios of 2020/2030

At future scenarios, the levelised electricity costs of photovoltaic can be reduced considerably to between 12 to 7 €-Cents at an interest rate of 6% (Table 69) mainly because of the change to the new 3<sup>rd</sup> generation technology. With increasing efficiencies and better plant operation, the necessary installation capacities are clearly decreasing: the PV capacity can be reduced to about 85% and the

installed power of the pumped hydroelectric storage plant to about 87 to 90% (with the exception at the lowest power level). The necessary storage capacity remains about the same with some variations at the smaller power levels, dependent on the exact configuration and conditions of the scenario. Thus, with the new and cheaper technology in 2020/2030 the fraction of the costs caused by power generation is shifted to a small amount towards transmission as well as storage and dumping.

Table 69. Calculations of base load for PV systems in 2020/2030.

| Demand                          | GW              | 0.5    | 5      | 10     | 100    | 150    |
|---------------------------------|-----------------|--------|--------|--------|--------|--------|
| <b>Assumptions</b>              |                 |        |        |        |        |        |
| Generation zone                 |                 | A1     | A1     | A3     | A3     | A3     |
| PV Capacity                     | GW <sub>p</sub> | 3      | 30     | 55     | 553    | 846    |
| Pumped Hydro                    | GW              | 2.25   | 21.93  | 36.86  | 369.02 | 567.18 |
| Storage Capacity                | GWh             | 60     | 700    | 230    | 3,000  | 3,500  |
| <b>Resulting LEC</b>            |                 |        |        |        |        |        |
| Interest rate 6 %               | €/kWh           | 0.123  | 0.115  | 0.087  | 0.068  | 0.066  |
| Interest rate 8 %               | €/kWh           | 0.144  | 0.137  | 0.103  | 0.081  | 0.079  |
| <b>LEC Breakdown for IR=6 %</b> |                 |        |        |        |        |        |
| PV generation                   |                 | 49.3 % | 39.5 % | 52.6 % | 45.7 % | 44.1 % |
| Transmission                    |                 | 8.2 %  | 10.1 % | 13.9 % | 15.0 % | 15.1 % |
| Storage and dumping             |                 | 42.5 % | 50.4 % | 33.5 % | 39.3 % | 40.7 % |

For future solar thermal systems in 2020/2030 the advancements in technology and plant operation will lead to LECs between 10 and 5 €-Cents for an interest rate of 6% (Table 70). As the technology of the solar thermal power plants is already rather mature, the necessary capacity of the power generation plant is decreasing here only 3 to 8% at about equal remaining storage capacities. Thus, more potential for a price reduction lies in the transmission lines and the external pumped hydroelectric storage, increasing at least at higher power levels the percentage of costs caused by the generation system from 65 to 70% comparing state-of-the-art technology with that of the years 2020/2030.

Table 70. Calculations or base load for ST systems in 2020/2030.

| Demand                         | GW               | 0.5    | 5      | 10     | 100    | 150    |
|--------------------------------|------------------|--------|--------|--------|--------|--------|
| <b>Assumptions</b>             |                  |        |        |        |        |        |
| Generation zone                |                  | A1     | A1     | A1/A1b | A3     | A3     |
| ST Capacity                    | GW <sub>el</sub> | 0.73   | 7.5    | 15.1   | 138.0  | 208.0  |
| Pumped Hydro                   | GW               | 0.5    | 5.0    | 10.0   | 31.9   | 47.6   |
| Storage Capacity               | GWh              | 70     | 605    | 530    | 255    | 375    |
| <b>Resulting LEC</b>           |                  |        |        |        |        |        |
| Interest rate 6 %              | €/kWh            | 0.095  | 0.080  | 0.071  | 0.051  | 0.050  |
| Interest rate 8 %              | €/kWh            | 0.110  | 0.093  | 0.083  | 0.059  | 0.057  |
| <b>LEC Breakdown for IR=6%</b> |                  |        |        |        |        |        |
| ST generation                  |                  | 65.3 % | 65.1 % | 68.5 % | 70.6 % | 70.1 % |
| Transmission                   |                  | 9.1 %  | 7.3 %  | 11.5 % | 17.5 % | 17.6 % |
| Storage and dumping            |                  | 25.5 % | 27.6 % | 20.0 % | 11.9 % | 12.3 % |

## 4.3 Provision of Peak Load

In the second work package the provision of remaining load is to be examined. After a short description on the findings about the optimization of the system configurations, the most important results for the remaining load are presented herein.

### 4.3.1 Comparison of Demand and Generation

Deviations of the demand load and the PV generation are shown in Figure 68 exemplary for one week in January. Whereas there is a steady but varying demand, high during the day and with another peak in the evening hours, the generating PV is able to deliver electricity only when irradiated hence during daytime. To cover also the demand at night, electricity production must exceed the demand during the day and be stored for the night. The characteristics within a week in summer show principally differing quantities but are qualitatively similar.

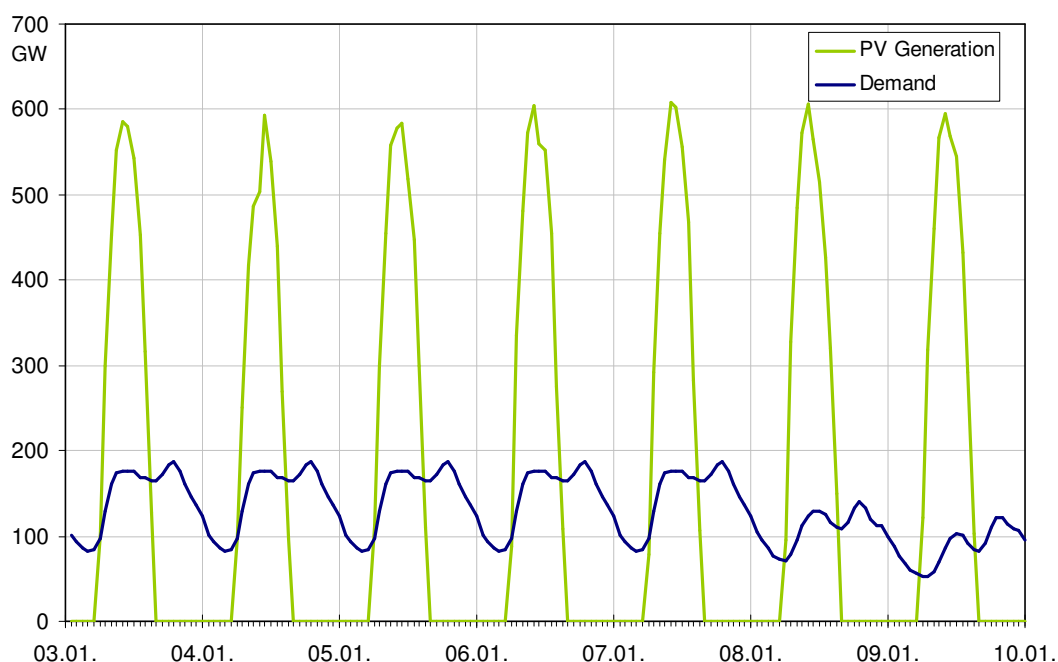


Figure 68. Demand and PV generation for the 100 GW scenario during one January week

To get an impression on the characteristics over the whole year, the photovoltaic generation of the 100 GW scenario is presented in Figure 69 at an inclination angle of the panels of  $60^\circ$  together with the corresponding demand curve. The regular breakdowns in the demand curve represent the weekends, where less electricity consumption takes place. It can be noticed that the generated power from the  $60^\circ$  inclined PV is following the shape of the demand curve but does not cover it completely: during 3 to 4 weeks in the summer a certain power capacity is lacking.

By keeping that tilt angle of  $60^\circ$  unchanged throughout the year, besides the lack of a full coverage of the demand curve one would throw away a considerable amount of attainable electricity, which could be gained by changing the tilt angle like in the base load case from  $60^\circ$  in winter to  $10^\circ$  in summer. Like this a uniform amount of power generation can be achieved throughout the year, which always covers the demand load. Produced electricity exceeding the demand probably will be used by other consumers when sold at a sufficiently low price. Therefore a price of 2 Cents/kWh today and 2.5 Cents per kWh in 2020/2030 is assumed. Thus, although 2% higher costs are calculated for the mounting with a changeable tilt angle, these higher costs are covered by far by electricity sold at those conditions. Finally, the scenarios for remaining load were calculated along the assumption of changing the tilt angle at the beginning of March and again at the beginning of October.

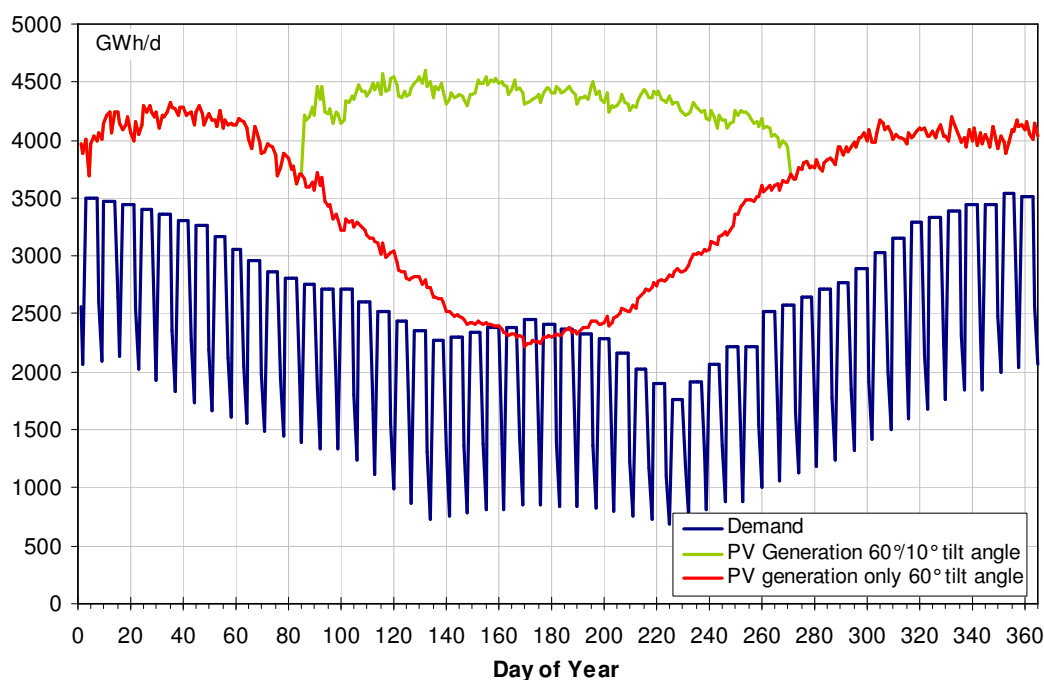


Figure 69. Daily demand and PV generation for the 100 GW scenario

For solar thermal power plants the collocation of the troughs in east-west direction was also taken here as over all it shows better efficiencies for remaining load, too.

#### 4.3.2 Summary of Results for Remaining-Load Scenarios of today

For the remaining load, four power levels have been calculated from 5 GW to 150 GW. The named amount of the power levels relate to the average of the taken load curve. The corresponding maximum, minimum and complete annual consumption are listed at the top of each table. Further important values are listed in a similar manner as for base load. Generation of electricity here was performed completely within zone A3 for PV as well as for solar thermal.

Table 71 shows the scenarios for the remaining load of today's photovoltaic system. An average power level of 5 GW corresponds to a maximal power peak of 9.5 GW and an annual consumption of 43.8 TWh, analogous at the higher power levels.

Required capacities for the PV panels are generally higher than in the base load case: 39 GW<sub>p</sub> of PV cells are necessary to cover the power demand of 5 GW in average, climbing up to 1,243 GW<sub>p</sub> for the 150 GW scenario. For the storage system the same characteristic can be noticed with storage capacities ranging from 380 to 6,000 GWh (only at the 5 GW load power the base load case is higher, however due to the different generation zone). Finally, levelised electricity costs between 24 Cents and 17 Cents are obtained for photovoltaic. The breakdown of the LEC shows that here at remaining load with values between 44 and 50% a considerable higher percentage of the LEC is caused by storage and dumping instead of 35 to 40% at the base load case. Generation remains at percentages up to 40%. The corresponding results for the solar thermal state-of-the-art scenarios are presented in Table 72. Here, for the 5 GW scenario a capacity of the solar thermal power plant of 11 GW<sub>el</sub> is required. Towards the scenario of 150 GW, the capacity of the solar thermal plant needs to be increased to 336 GW<sub>el</sub>. No external pumped hydroelectric storage was necessary as complete storing could be done by the on-site thermal storage. Thus, levelised electricity costs with 8 to 6 Cents could

be achieved for solar thermal for an interest rate of 6%. These values are similar to the corresponding base load case but significantly lower than the LEC of the state-of-the-art photovoltaic of Table 71. The breakdown of the costs shows that an amount of about 55% of the LEC is caused by the generation of electricity, including the thermal storage, and the rest due to dumping of exceeding energy and transmission of the electricity to the supply zone.

Table 71. Calculations of remaining load for PV systems today

| <b>Demand</b>                  |                 |        |        |        |         |
|--------------------------------|-----------------|--------|--------|--------|---------|
| Average                        | GW              | 5.0    | 10.0   | 100.0  | 150.0   |
|                                | TWh             | 43.8   | 87.6   | 876.0  | 1,314.0 |
| Maximum                        | GW              | 9.5    | 18.9   | 189.5  | 284.3   |
| Minimum                        | GW              | 0      | 0      | 0      | 0       |
| <b>Assumptions</b>             |                 |        |        |        |         |
| Generation zone                |                 | A3     | A3     | A3     | A3      |
| PV Capacity                    | GW <sub>p</sub> | 39     | 77     | 876    | 1,243   |
| Pumped Hydro                   | GW              | 28.68  | 56.55  | 613.27 | 919.50  |
| Storage Capacity               | GWh             | 380    | 890    | 4,000  | 6,000   |
| <b>Resulting LEC</b>           |                 |        |        |        |         |
| Interest rate 6%               | €/kWh           | 0.235  | 0.219  | 0.180  | 0.173   |
| Interest rate 8%               | €/kWh           | 0.276  | 0.257  | 0.212  | 0.204   |
| <b>LEC Breakdown for IR=6%</b> |                 |        |        |        |         |
| PV generation                  |                 | 40.4 % | 40.0 % | 35.4 % | 34.9 %  |
| Transmission                   |                 | 15.3 % | 15.1 % | 14.8 % | 14.8 %  |
| Storage and dumping            |                 | 44.3 % | 44.9 % | 49.8 % | 50.2 %  |

Table 72. Calculations of remaining load for ST systems today

| Demand                     |                  | GW     |        |        |         |
|----------------------------|------------------|--------|--------|--------|---------|
| Average                    | GW               | 5.0    | 10.0   | 100.0  | 150.0   |
|                            | TWh              | 43.8   | 87.6   | 876.0  | 1,314.0 |
| Maximum                    | GW               | 9.5    | 18.9   | 189.5  | 284.3   |
| Minimum                    | GW               | 0      | 0      | 0      | 0       |
| Assumptions                |                  |        |        |        |         |
| Generation zone            |                  | A3     | A3     | A3     | A3      |
| ST Capacity                | GW <sub>el</sub> | 11.2   | 22.3   | 223.6  | 335.5   |
| Pumped Hydro               | GW               | 0      | 0      | 0      | 0       |
| Resulting LEC              |                  |        |        |        |         |
| Interest rate 6%           | €/kWh            | 0.081  | 0.070  | 0.058  | 0.057   |
| Interest rate 8%           | €/kWh            | 0.095  | 0.082  | 0.069  | 0.067   |
| LEC Breakdown<br>for IR=6% |                  |        |        |        |         |
| ST generation              |                  | 54.4 % | 55.6 % | 57.0 % | 57.4 %  |
| Transmission and dumping   |                  | 45.6 % | 44.4 % | 43.0 % | 42.6 %  |

### 4.3.3 Summary of Remaining-Load Scenarios in 2020/2030

The results for the future remaining load scenarios are listed in Table 73 for the PV system and in Table 74 for solar thermal. At the demand side, again the same values were taken within the future scenario for the underlying average, maximum and minimum values of the remaining load and for the corresponding consumption. Also as generation zone the zone A3 was selected only.



Table 73. Calculations of remaining load for PV systems in 2020/2030

| <b>Demand</b>                  |                 |        |        |        |         |
|--------------------------------|-----------------|--------|--------|--------|---------|
| Average                        | GW              | 5.0    | 10.0   | 100.0  | 150.0   |
|                                | TWh             | 43.8   | 87.6   | 876.0  | 1,314.0 |
| Maximum                        | GW              | 9.5    | 18.9   | 189.5  | 284.3   |
| Minimum                        | GW              | 0      | 0      | 0      | 0       |
| <b>Assumptions</b>             |                 |        |        |        |         |
| Generation zone                |                 | A3     | A3     | A3     | A3      |
| PV Capacity                    | GW <sub>p</sub> | 33     | 67     | 704    | 1,056   |
| Pumped Hydro                   | GW              | 25.26  | 51.36  | 542.53 | 813.79  |
| Storage Capacity               | GWh             | 410    | 665    | 4,000  | 6,000   |
| <b>Resulting LEC</b>           |                 |        |        |        |         |
| Interest rate 6%               | €/kWh           | 0.117  | 0.108  | 0.082  | 0.080   |
| Interest rate 8%               | €/kWh           | 0.140  | 0.129  | 0.100  | 0.097   |
| <b>LEC Breakdown for IR=6%</b> |                 |        |        |        |         |
| PV generation                  |                 | 39.6 % | 37.7 % | 30.4 % | 29.6 %  |
| Transmission                   |                 | 16.1 % | 16.4 % | 16.7 % | 16.6 %  |
| Storage and dumping            |                 | 44.3 % | 45.9 % | 53.0 % | 53.8 %  |

Analogous to the base load case, the required PV capacity is reduced when future and more efficient technology in the complete PV system is used. So for the 5 GW scenario a PV capacity of 33 GW<sub>p</sub> (instead of 39 GW<sub>p</sub>) is sufficient. For the power level of 150 GW 1,056 GW<sub>p</sub> is required, instead of 1,243 GW<sub>p</sub>. This accounts to a reduction in PV capacity of 15%. The power level needed for the pumped hydrogen storage is also lower to an amount of about 10 to 12% whereas the needed storage capacity accounts for about the same amounts. The LEC however decreases considerably by the introduction of the new technology to an amount between 12 Cent/kWh for the smaller power levels and 8 Cents/kWh for the 150 GW scenario with an interest rate of 6%. Looking on the cost breakdown, at higher power levels an amount of about 5% caused formerly by the generation system is shifted to transmission and storage system respectively dumping.

Table 74. Calculations for ST systems in 2020/2030

| <b>Demand</b>                  |                  |        |        |        |         |
|--------------------------------|------------------|--------|--------|--------|---------|
| Average                        | GW               | 5.0    | 10.0   | 100.0  | 150.0   |
|                                | TWh              | 43.8   | 87.6   | 876.0  | 1,314.0 |
| Maximum                        | GW               | 9.5    | 18.9   | 189.5  | 284.3   |
| Minimum                        | GW               | 0      | 0      | 0      | 0       |
| <b>Assumptions</b>             |                  |        |        |        |         |
| Generation zone                |                  | A3     | A3     | A3     | A3      |
| ST Capacity                    | GW <sub>el</sub> | 10.8   | 21.6   | 216.0  | 324.1   |
| Pumped Hydro                   | GW               | 0      | 0      | 0      | 0       |
| <b>Resulting LEC</b>           |                  |        |        |        |         |
| Interest rate 6%               | €/kWh            | 0.060  | 0.056  | 0.047  | 0.046   |
| Interest rate 8%               | €/kWh            | 0.072  | 0.067  | 0.057  | 0.055   |
| <b>LEC Breakdown for IR=6%</b> |                  |        |        |        |         |
| ST generation                  |                  | 62.5 % | 63.5 % | 66.2 % | 66.8 %  |
| Transmission and dumping       |                  | 37.5 % | 36.5 % | 33.8 % | 33.2 %  |

The capacity necessary for future solar power plants in 2020/2030 is also decreasing due to progress in its technology but only to an amount of 3 and 3.5%. In this case, the technology is assumed to be much more mature. Additional external storage is not necessary here either. Thus, at an interest rate of 6% the levelised electricity costs are reduced to 6 Cents for smaller power levels and even below 5 Cents for full supply. As a higher price reduction can be achieved at the transmission lines than in the power plant technology, a higher percentage of around 65% of the costs then will be caused by the solar thermal generation system.

#### 4.4 Conclusions on the terrestrial scenarios

A full power supply of West- and Central Europe is possible with terrestrial solar power plants. The solar power plants are assumed to be placed in Northern Africa because of the significantly higher annual irradiation amount and more and easier available ground areas, so far not considering political conditions and risks.

It could be shown that by a sophisticated collocation and configuration of the power plants no seasonal storage is needed. Neither for base load nor for remaining load high storage capacities are required, so cheap high efficiency pumped hydroelectric storage plants can cover the storage demand for all scenarios. However, high excess generation in summer occurs. Exceeding energy has to be dumped or might even be sold at different conditions.

Thus in 2020/2030, terrestrial solar electricity generated at optimal sites in Africa can be competitive even to conventional power systems for ensuring a climatic sustainable power supply. This is true for a constant base load throughout the year but even for remaining load with a peak in winter.

## 5 Combination of terrestrial and space based systems

The aim of work package 3 was the combination of Space Power Satellites and terrestrial systems in order to get clear possible advantages of such a combination of both systems. After the specification of underlying assumptions, the results for four scenarios, examined in detail, will be presented.

### 5.1 Definitions for combined scenarios

As SPS is only an option for the future and not yet for today, all calculations for the combined scenarios are performed only for the 2020/2030 case and according to work package 2 all within generation zone A3. All calculations refer to the demand load curve presented in paragraph 0 (respectively Figure 41 and Figure 42), combining base and remaining load, which has been scaled from UCTE to all Zones B-U by a factor 136.2% and adapted to the year 2020 by an assumed annual growth rate of 1.5%. This yields the demand values shown in Table 75.

Table 75. Demand loads for the combined scenario: UCTE load curves scaled by 136.2% to Zones B-U and adapted to the year 2020 by an annual growth rate of 1.5%

| Minimum load / GW | Average load / GW | Maximum load / GW | Demand sum / TWh |
|-------------------|-------------------|-------------------|------------------|
| 266               | 439               | 593               | 3843             |

The combination of SPS and terrestrial power supply investigated within this work package concerns the transfer of the power from space by laser beam and using a photovoltaic receiver at ground to capture the power of the laser beam as well as incident solar irradiation. Additional terrestrial PV is placed to cover the remaining difference to the hourly course of the load curve, which is increasing during daytime hours. Still remaining differences are compensated by a storage system. The ground receiver for the SPS is also located in zone A3 in vicinity to the terrestrial PV, where the transmittance of the atmosphere for the laser beam is estimated according to the cloud cover fraction from the Meteonorm weather data.

To get the best combination of the amounts of the space respectively terrestrial PV modules and to dimension the storage system appropriately, an optimization of the installed capacities has been performed with minimization of the LEC as crucial parameter. The following scenarios have been investigated in detail:

- S-1) SPS was modelled along the characteristics outlined by EADS. The panels of the ground receiver are inclined optimally for the fix incidence angle of the laser beam of 32° with a row spacing optimized to cover the whole receiver area as seen from the SPS. The additional terrestrial PV has been modelled as in work packages 1 and 2, optimized for solar irradiation at ground at the respective site with the 60°/10° tilt angles of the PV modules for winter/summer. As storage system also pumped hydroelectric was used as in work packages 1 and 2.

- S-2) Compared with scenario 1, the storage system has been changed to hydrogen storage by means of a pressure vessel instead of the pumped water storage. Modelling of space and terrestrial PV has been performed as outlined in scenario 1.
- S-3) The complete PV on ground has been performed optimized for the laser beam to have the freedom to select and send the laser beams to the sites with the highest atmospheric transmittance.
- S-4) The complete PV on ground has been performed for an optimal terrestrial outcome from solar irradiation with 60°/10° tilt angles of the PV. The distance between the rows is 1.8 times the module width in order to get minimal shading losses at justifiable land needs. This scenario reflects a primarily set up of terrestrial PV power plants with later added-on SPS plants.

For scenarios 1) and 2) also calculations with 5 and 10 times the originally stated transportation costs of 530 €/kg have been performed. Figure 70 shows the demand load curve and the generated power by a selected combined space-terrestrial power plant for one week during wintertime, split into the different power sources. As combined plant for the calculations a configuration of 60 SPS systems, its respective ground receiver and additional 533 GW<sub>p</sub> of terrestrial PV were selected. The pumped hydro storage has a capacity of 9025 GWh. For several numbers of SPS systems the additionally necessary terrestrial PV as well as the necessary storage capacity has been optimized to the lowest LEC.

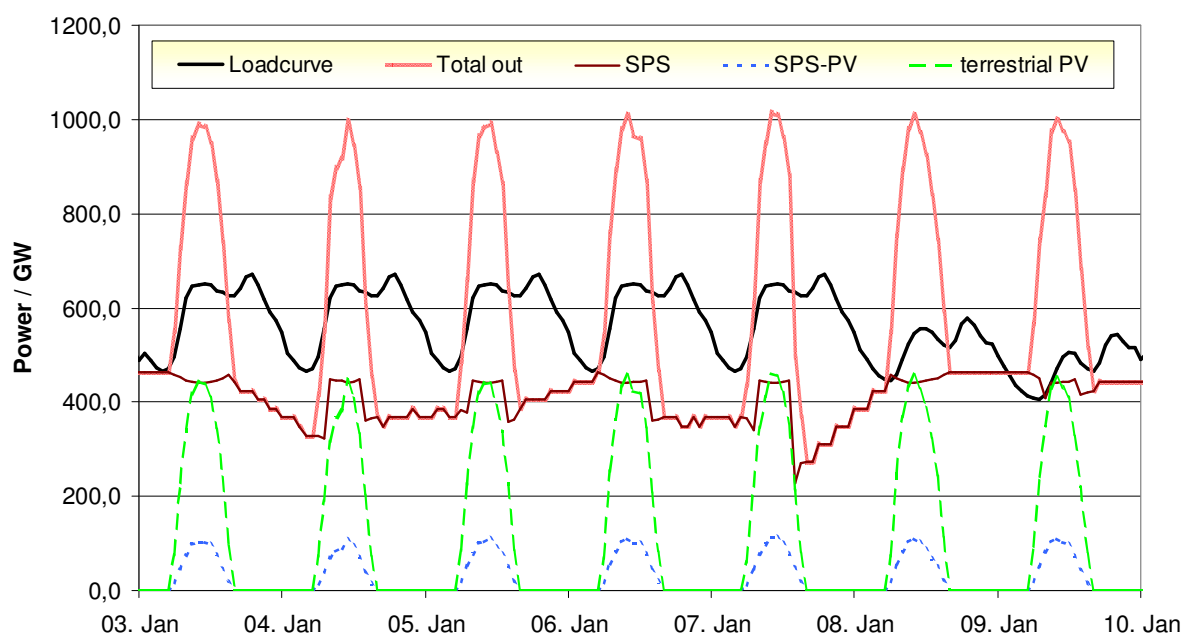


Figure 70. Power output of a combined SPS-terrestrial power plant according to scenario 1 for 60 SPS systems and 533 GW<sub>p</sub> terrestrial PV and 9025 GWh storage capacity

Table 76 shows the cost assumptions for the SPS system for several numbers up to 90 SPS plants. The table shows specific costs for one SPS as well as the summarized costs for the complete number of SPS, split in the different types of the cost sources. The most expensive part of the space system belongs to the transportation of the SPS system to space. Here, transportation costs of 530 € per kg payload were assumed after some space flights at the beginning of the project. This is about 1/10 to 1/20 of the today costs.

Table 76. Cost assumptions for the SPS system

| Number of SPS                        | 1            | 15            | 30            | 45            | 60            | 75            | 90            |                    |
|--------------------------------------|--------------|---------------|---------------|---------------|---------------|---------------|---------------|--------------------|
| Space PV capacity                    | 22.1         | 332.1         | 664.2         | 996.3         | 1328.4        | 1660.5        | 1992.6        | GW <sub>p</sub>    |
| <b>Specific costs per SPS</b>        |              |               |               |               |               |               |               |                    |
| PV costs per kW <sub>p</sub>         | 1869,4       | 834.9         | 724.7         | 690.2         | 666.7         | 649.0         | 634.9         | B€/kW <sub>p</sub> |
| PV costs per SPS                     | 41.4         | 18.5          | 16.0          | 15.3          | 14.8          | 14.4          | 14.1          | B€/SPS             |
| Conc.&Control                        | 11.5         | 4.8           | 4.1           | 3.9           | 3.7           | 3.6           | 3.6           | B€/SPS             |
| Laser                                | 8.8          | 3.7           | 2.9           | 2.6           | 2.4           | 2.2           | 2.1           | B€/SPS             |
| Transport                            | 55.3         | 36.6          | 33.0          | 31.0          | 29.7          | 28.7          | 27.9          | B€/SPS             |
| Financing                            | 7.8          | 4.3           | 3.8           | 3.5           | 3.4           | 3.3           | 3.2           | B€/SPS             |
| <b>Specific SPS costs</b>            | <b>124,8</b> | <b>67,9</b>   | <b>59,8</b>   | <b>56,3</b>   | <b>53,9</b>   | <b>52,2</b>   | <b>50,8</b>   | <b>B€/SPS</b>      |
| <b>Summarized costs over all SPS</b> |              |               |               |               |               |               |               |                    |
| Space Plant                          | 61.7         | 404.6         | 691.9         | 978.5         | 1251.8        | 1515.8        | 1772.5        | B€                 |
| Transport                            | 55.3         | 549.6         | 989.3         | 1395.2        | 1780.7        | 2151.6        | 2511.4        | B€                 |
| Financing                            | 7.8          | 63.9          | 112.6         | 159.0         | 203.2         | 245.7         | 287.0         | B€                 |
| <b>SPS costs</b>                     | <b>124.8</b> | <b>1018.2</b> | <b>1793.8</b> | <b>2532.8</b> | <b>3235.7</b> | <b>3913.1</b> | <b>4570.9</b> | <b>B€</b>          |

## 5.2 Scenario 1: Optimized scenario

The results of the optimized scenario S-1 are presented for several selected combination levels in Table 77. At a minimum of 77 SPS systems no additional terrestrial PV is needed to cover the total power supply, hence this configuration representing the “SPS only” case (left side column). In contrary, without SPS a terrestrial PV capacity of 2621 GW<sub>p</sub> is needed to completely cover the demand load, accounting to 100% terrestrial generation ratio, “terrestrial only” at the right side column. The “SPS only” case of 77 SPS does not account on a 100% SPS generation ratio but only 92.3% because the ground receiver contributes the remaining 7.7% generated by daylight conversion at ground. The columns in between show results of combined space-terrestrial scenarios with an augmenting terrestrial portion from left to the right. As the capacity of the SPS ground receiver is low compared to the terrestrial PV, it has been assumed that within this optimized scenario all SPS receivers are installed within the region of the lowest cloud coverage (Luxor, El Kharga, Aswan).

Table 77. Calculations for combined scenario 1 with transportation costs of 530 €/kg

| Combination level            | SPS only | ...   | combined | ...   | terrestrial only |                      |
|------------------------------|----------|-------|----------|-------|------------------|----------------------|
| <b>Number of SPS</b>         | 77       | 60    | 45       | 30    | 15               | 0                    |
| Space PV installation        | 1705     | 1328  | 996      | 664   | 332              | 0 GW <sub>p</sub>    |
| Max SPS ground out           | 605      | 471   | 353      | 236   | 118              | 0 GW <sub>p</sub>    |
| SPS generation               | 4832     | 3764  | 2823     | 1882  | 941              | 0 TWh                |
| SPS generation ratio         | 92.3%    | 71.9% | 53.0%    | 34.7% | 17.0%            | 0%                   |
| <b>SPS-PV receiver</b>       |          |       |          |       |                  |                      |
| PV installation              | 221      | 170   | 127      | 85    | 42               | 0 GW <sub>p</sub>    |
| Generation                   | 403      | 310   | 233      | 155   | 78               | 0 TWh                |
| SPS-PV gen. ratio            | 7.7%     | 5.9%  | 4.4%     | 2.9%  | 1.4%             | 0%                   |
| <b>Terrestrial PV</b>        |          |       |          |       |                  |                      |
| PV installation              | 0        | 533   | 1044     | 1556  | 2069             | 2621 GW <sub>p</sub> |
| Generation                   | 0        | 1163  | 2276     | 3391  | 4510             | 5715 TWh             |
| Terr. generation ratio       | 0%       | 22.2% | 42.7%    | 62.5% | 81.6%            | 100%                 |
| <b>Storage: Pumped hydro</b> |          |       |          |       |                  |                      |
| Max. storage in/out          | 366      | 614   | 908      | 1203  | 1499             | 1828 GW              |
| Storage Capacity             | 7309     | 9025  | 10054    | 11096 | 12166            | 12475 GWh            |
| Storage usage                | 99       | 392   | 854      | 1364  | 1880             | 2396 TWh             |
| Total generation             | 5236     | 5238  | 5332     | 5429  | 5528             | 5715 TWh             |
| Dumping                      | 755      | 705   | 716      | 725   | 734              | 825 TWh              |
| <b>Resulting LEC</b>         |          |       |          |       |                  |                      |
| Interest rate 6%             | 0.092    | 0.088 | 0.085    | 0.080 | 0.075            | 0.065 €/kWh          |
| <b>LEC Breakdown</b>         |          |       |          |       |                  |                      |
| Generation                   | 64.6%    | 61.3% | 56.3%    | 50.9% | 44.8%            | 35.1%                |
| SPS                          | 61.7%    | 52.4% | 42.0%    | 30.9% | 18.6%            | 0%                   |
| SPS-PV                       | 2.9%     | 2.1%  | 1.5%     | 1.0%  | 0.5%             | 0%                   |
| Terrestrial PV               | 0%       | 6.9%  | 12.9%    | 19.0% | 25.7%            | 35.1%                |
| Transmission                 | 16.1%    | 16.1% | 16.0%    | 15.8% | 15.8%            | 16.1%                |
| Storage and dumping          | 19.3%    | 22.6% | 27.7%    | 33.3% | 39.4%            | 48.8%                |

Table 77 shows that for a pure space solution a capacity of 1705 GW<sub>p</sub> has to be placed in space with an additional ground receiver capacity of 221 GW<sub>p</sub> to capture the laser beam. From the 1705 GW<sub>p</sub> generated in space, only 605 GW<sub>p</sub> are fed into the electricity grid at the ground receiver. Throughout the year the SPS produce 4832 TWh plus 403 TWh coming from daylight ground irradiation, resulting in totally 5236 TWh. As there is no (additional) terrestrial collocated at the “SPS only” case, there is no contribution. Nonetheless of a steady power generation in space, a pumped hydroelectric storage capacity of 7309 GWh is necessary with a maximal input respectively output power of 366 GW. This storage capacity is required to cover the (scarce) cloudy periods in the desert. 99 TWh were put into and out of storage throughout the year whereas 755 TWh have to be dumped respectively sold at a cheaper price of 2.5 Cents per kWh. This configuration results in a LEC of 9.2 Cent/kWh at an interest

rate of 6%. 65% of this amount is caused by the generation system, 16% by the transmission lines and 19% due to storage and dumping.

For the “terrestrial only” case no SPS is installed. Terrestrial photovoltaic needs a capacity of 2621 GWp, which is 36% more than at SPS only, thus producing 5715 TWh annually. This is due to the considerably higher storage need where a capacity of 12475 TWh at a maximal input/output power of 1828 GW is required. This means 5 times the charge/discharge power and a 70% higher storage capacity due to the fact that electricity produced during daytime has to be stored for the night hours when solar irradiation is missing. Instead of 99 TWh at the space only solution, here at pure terrestrial 2396 TWh were sent to and taken from the pumped hydroelectric storage, which is 24 times more. Dumped energy of 825 TWh account a 10% higher value. However, the LEC are lower with 6.5 Cents per kWh. The high storage use is also noticed in the cost breakdown where only 35% account to power generation, whereas nearly half the costs are due to buffering and dumping.

The configurations of the different combination levels, its corresponding optimised capacities and outcomes show values in between. Their detailed results can be found in Table 77 as well as graphically illustrated in Figure 71, Figure 72 as well as Figure 75 and Figure 76. Launching costs are one of the most crucial points of the space system. High efforts and advances are necessary to reach the assumed costs of 530 €/kg. Thus further calculations were made with five and ten times higher transportation costs at start off of an SPS project. The results are shown in Table 78 and Table 79.

Table 78. Calculation of combined scenario 1 with 5 times higher transportation costs:  
2560 €/kg

| Combination level      | SPS only | ...   | combined | ...   | terrestrial only |             |
|------------------------|----------|-------|----------|-------|------------------|-------------|
| Number of SPS          | 77       | 60    | 45       | 30    | 15               | 0           |
| Terr. generation ratio | 0%       | 22.2% | 42.7%    | 62.5% | 81.6%            | 100%        |
| <b>Resulting LEC</b>   |          |       |          |       |                  |             |
| Interest rate 6%       | 0.284    | 0.244 | 0.207    | 0.167 | 0.123            | 0.065 €/kWh |
| <b>LEC Breakdown</b>   |          |       |          |       |                  |             |
| Generation             | 70.6%    | 69.0% | 65.6%    | 61.3% | 54.4%            | 35.1%       |
| SPS                    | 69.6%    | 65.8% | 59.7%    | 51.6% | 38.5%            | 0%          |
| SPS-PV                 | 0.9%     | 0.7%  | 0.6%     | 0.5%  | 0.3%             | 0%          |
| Terrestrial PV         | 0%       | 2.5%  | 5.3%     | 9.2%  | 15.7%            | 35.1%       |
| Transmission           | 12.9%    | 13.1% | 13.1%    | 13.3% | 13.8%            | 16.1%       |
| Storage and dumping    | 16.5%    | 17.9% | 21.3%    | 25.4% | 31.7%            | 48.8%       |

Table 79. Calculations of combined scenario 1 with 10 times higher transportation costs:  
5300 €/kg

| Combination level      | SPS only | ...   | combined | ...   | terrestrial only |             |
|------------------------|----------|-------|----------|-------|------------------|-------------|
| Number of SPS          | 76       | 60    | 45       | 30    | 15               | 0           |
| Terr. generation ratio | 0%       | 22.2% | 42.7%    | 62.5% | 81.6%            | 100%        |
| <b>Resulting LEC</b>   |          |       |          |       |                  |             |
| Interest rate 6%       | 0.519    | 0.438 | 0.359    | 0.275 | 0.183            | 0.065 €/kWh |
| <b>LEC Breakdown</b>   |          |       |          |       |                  |             |
| Generation             | 72.4%    | 70.9% | 68.3%    | 65.0% | 59.4%            | 35.1%       |
| SPS                    | 71.8%    | 69.1% | 65.0%    | 59.1% | 48.6%            | 0%          |
| SPS-PV                 | 0.5%     | 0.4%  | 0.4%     | 0.3%  | 0.2%             | 0%          |
| Terrestrial PV         | 0%       | 1.4%  | 3.0%     | 5.6%  | 10.5%            | 35.1%       |
| Transmission           | 12.3%    | 12.3% | 12.3%    | 12.4% | 12.8%            | 16.1%       |
| Storage and dumping    | 15.4%    | 16.7% | 19.4%    | 22.6% | 27.8%            | 48.8%       |

With only changing transportation costs, the necessary capacities for SPS, ground PV or storage do not change notably with respect to Table 77 and are therefore not listed once again. The costs at the pure terrestrial solution of course stays unchanged, too. However, with an augmenting space share the levelised electricity costs are dramatically increasing to 28 Cent/kWh for transportation costs of 2650 €/kg respectively 52 Cent/kWh for 5300 €/kg at the pure space scenario. This is noticed subsequently in the cost breakdown by a rising percentage for power generation by SPS, lowering transport, storage and dumping. The results are also graphically illustrated in Figure 71 as well as Figure 73 and Figure 74.

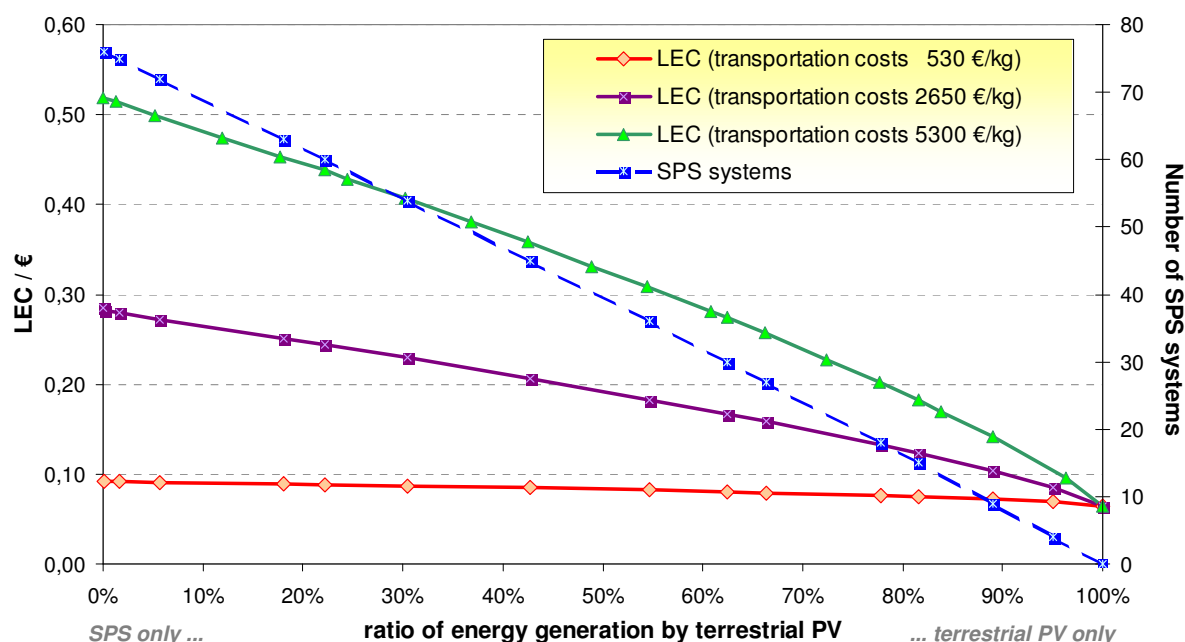


Figure 71. LEC of combined scenario 1 in dependence on the ratio of SPS- and terrestrial PV energy generation for several transportation costs



Whereas at transportation costs of 530 €/kg the LEC of the combined scenarios is in the same order of magnitude for all combination shares, it is considerably increasing for higher transportation costs.

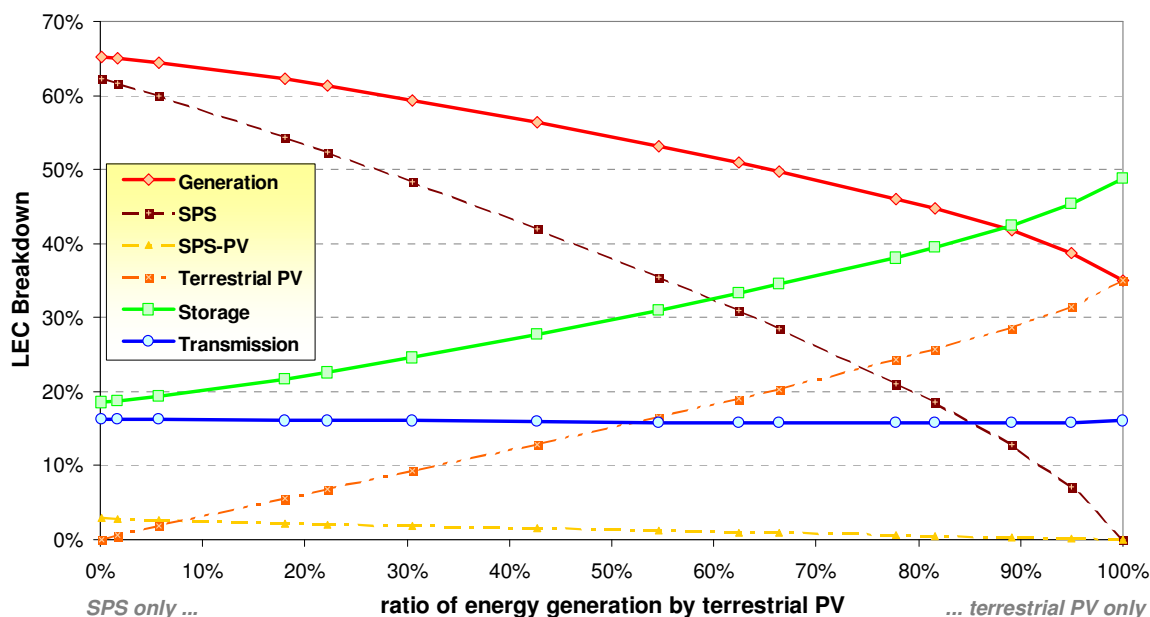


Figure 72. LEC breakdown of combined scenario 1 in dependence on the ratio of SPS- and terrestrial PV energy generation with launch costs of 530 €/kg

At the cost breakdown for pure space the major part is due to plant and transportation costs clearly at the generation side. With a growing portion of terrestrial PV this high share for generation costs is decreasing at a simultaneously increasing percentage of the storage until for pure terrestrial power supply the share of the storage exceeds that of generation costs.

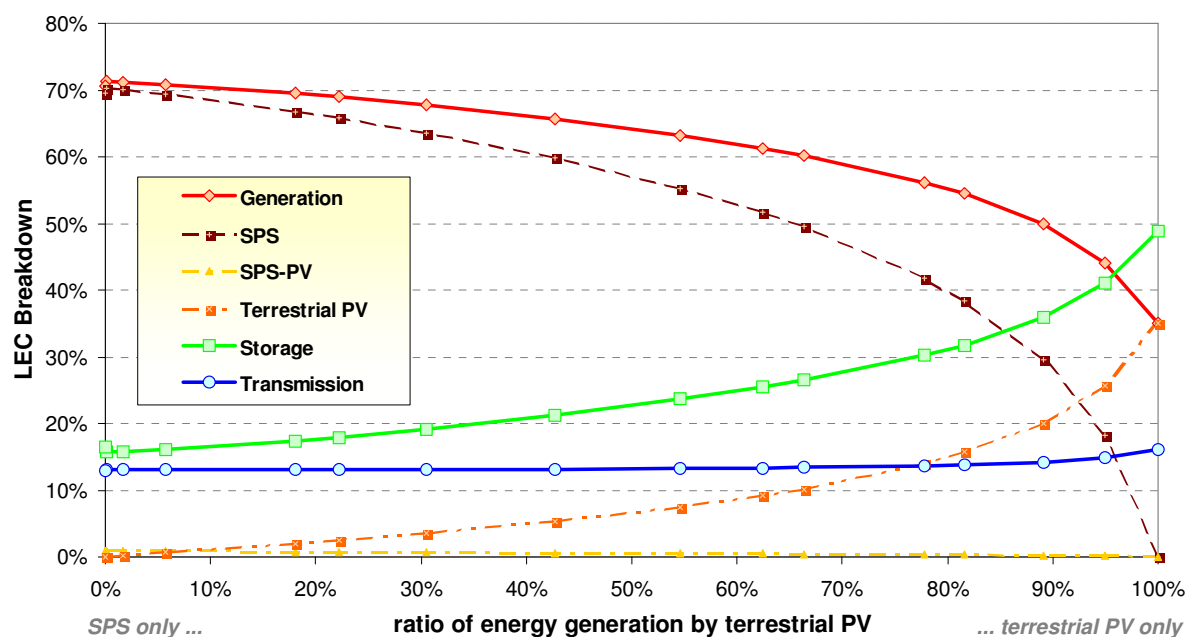


Figure 73. LEC breakdown of combined scenario 1 in dependence on the ratio of SPS- and terrestrial PV energy generation with launch costs of 2650 €/kg

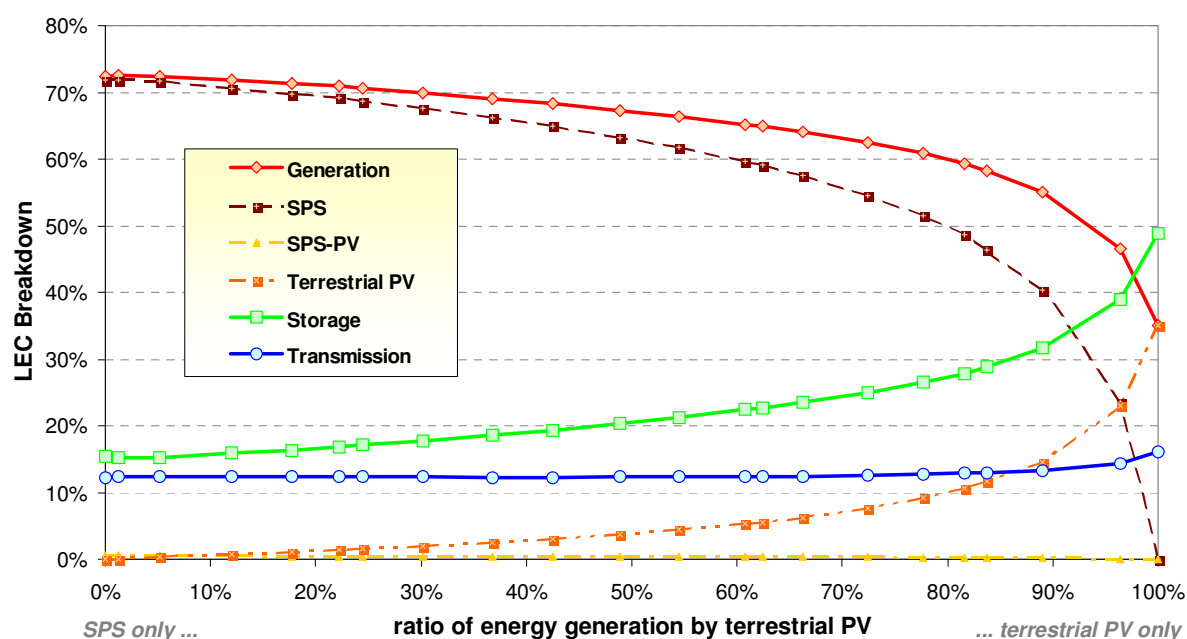


Figure 74. LEC breakdown of combined scenario 1 in dependence on the ratio of SPS- and terrestrial PV energy generation with launch costs of 5300 €/kg

Figure 75 shows the linear decrease of the peak power installation in space, its corresponding output at ground as well as the peak power, which needs to be installed as ground receiver for capturing the laser beams. At the same time the terrestrial peak power installation has to increase as well as the necessary maximal power of storage input or output.

In a similar way Figure 76 illustrates the annual amounts of generated energies split to the different sources as well as the amount of energy, which has to be dumped (sold to a lower price), the amount

which was put into and taken from the pumped hydro storage as well as the necessary capacity of the storage reservoir.

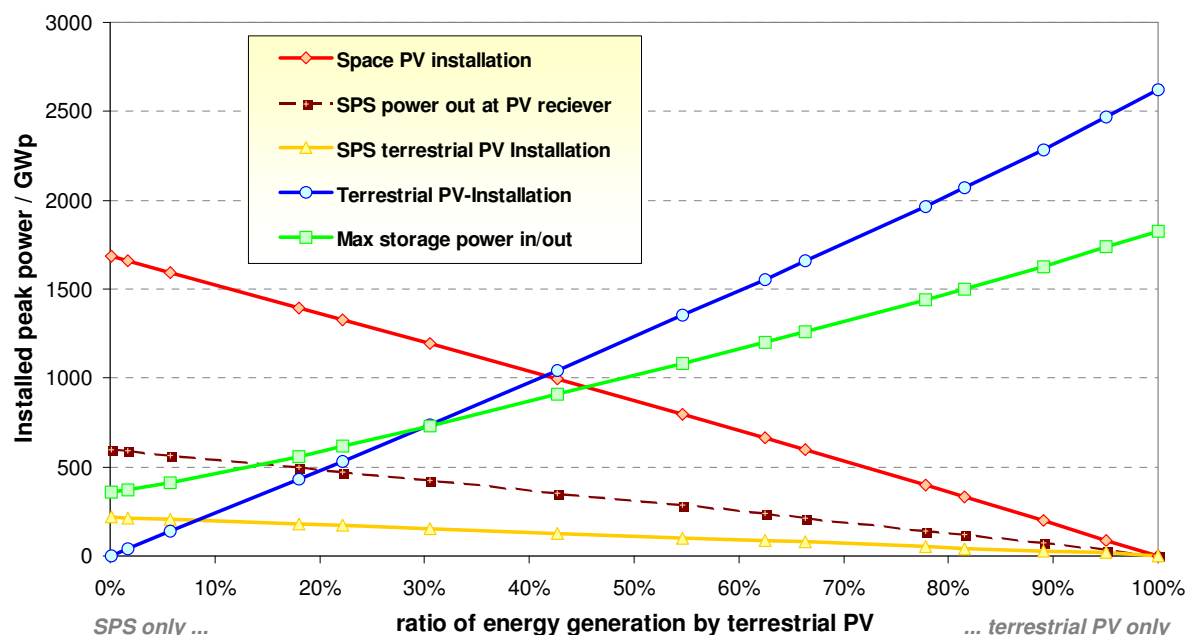


Figure 75. Installed power capacities and maximal power from the SPS ground receiver and power into or out of storage in dependence on the ratio of SPS- and terrestrial PV energy generation for combined scenario 1

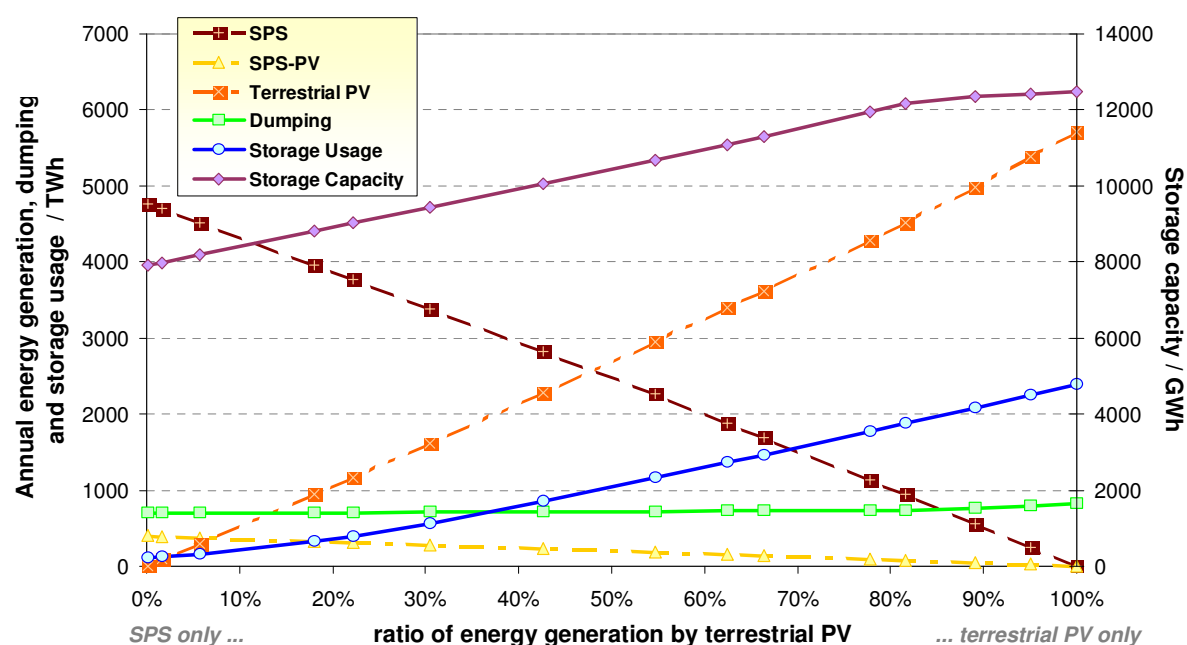


Figure 76. Annual sums of generated energy split for all of the three sources as well as dumped energy, storage usage and the storage capacity in dependence on the ratio of SPS and terrestrial PV for the combined scenario 1

### 5.3 Scenario 2: Hydrogen pressure vessel storage

At the second scenario (S-2), the pumped hydroelectric storage was replaced by hydrogen production and storage within a pressure vessel. By need of power it is re-converted to electricity by fuel cells or by a combined cycle power plant. This depicts the scenario of a more expensive storage system for the case that pumped hydroelectric storage is not applicable. All further assumptions remained as in scenario S-1. The results are presented in analogous manner in Table 80 for transportation costs of 530 €/kg.

Table 80. Calculations for combined scenario 2 with transportation costs of 530 €/kg

| Combination level                             | SPS only | ...   | combined | ...    | terrestrial only |                         |
|-----------------------------------------------|----------|-------|----------|--------|------------------|-------------------------|
| <b>Number of SPS</b>                          | 83       | 60    | 45       | 30     | 15               | 0                       |
| Space PV installation                         | 1838     | 1328  | 996      | 664    | 332              | 0 GW <sub>p</sub>       |
| Max SPS ground out                            | 652      | 471   | 353      | 236    | 118              | 0 GW <sub>p</sub>       |
| SPS generation                                | 5209     | 3764  | 2823     | 1882   | 941              | 0 TWh                   |
| SPS generation ratio                          | 92.3%    | 58.5% | 38.2%    | 22.6%  | 10.0%            | 0%                      |
| <b>SPS-PV receiver</b>                        |          |       |          |        |                  |                         |
| PV installation                               | 238      | 170   | 127      | 85     | 42               | 0 GW <sub>p</sub>       |
| Generation                                    | 434      | 310   | 223      | 155    | 78               | 0 TWh                   |
| SPS-PV gen. ratio                             | 7.7%     | 4.8%  | 3.1%     | 1.9%   | 0.8%             | 0%                      |
| <b>Terrestrial PV</b>                         |          |       |          |        |                  |                         |
| PV installation                               | 0        | 1084  | 1987     | 2893   | 3832             | 4844 GW <sub>p</sub>    |
| Generation                                    | 0        | 2363  | 4332     | 6306   | 8354             | 10561 TWh               |
| Terr. generation ratio                        | 0%       | 36.7% | 58.6%    | 75.6%  | 89.1%            | 100%                    |
| <b>Storage: H<sub>2</sub> pressure vessel</b> |          |       |          |        |                  |                         |
| Max. storage in/out                           | 420      | 1082  | 1710     | 2339   | 2998             | 3718 GW <sub>el</sub>   |
| H <sub>2</sub> storage capacity               | 9069     | 13904 | 15739    | 17568  | 19033            | 19503 GWh <sub>H2</sub> |
| Number of H <sub>2</sub> vessels              | 61274    | 93947 | 106346   | 118704 | 128603           | 131776                  |
| El <sub>out</sub> storage capacity            | 4988     | 7647  | 8657     | 9662   | 10468            | 10727 GWh <sub>el</sub> |
| Storage usage                                 | 49       | 378   | 828      | 1321   | 1815             | 2309 TWh <sub>el</sub>  |
| Total generation                              | 5643     | 6438  | 7388     | 8343   | 9373             | 10561 TWh <sub>el</sub> |
| Dumping                                       | 1083     | 1272  | 1401     | 1463   | 1592             | 1870 TWh <sub>el</sub>  |
| <b>Resulting LEC</b>                          |          |       |          |        |                  |                         |
| Interest rate 6%                              | 0.098    | 0.100 | 0.105    | 0.108  | 0.111            | 0.108 €/kWh             |
| <b>LEC Breakdown</b>                          |          |       |          |        |                  |                         |
| Generation                                    | 58.6%    | 46.5% | 37.2%    | 30.2%  | 24.3%            | 18.5%                   |
| SPS                                           | 56.0%    | 36.5% | 24.0%    | 14.7%  | 7.3%             | 0%                      |
| SPS-PV                                        | 2.6%     | 1.3%  | 0.8%     | 0.4%   | 0.2%             | 0%                      |
| Terrestrial PV                                | 0%       | 8.7%  | 12.5%    | 15.0%  | 16.8%            | 18.5%                   |
| Transmission                                  | 12.3%    | 12.3% | 12.3%    | 12.4%  | 12.8%            | 16.1%                   |
| Storage and dumping                           | 26.6%    | 40.1% | 50.5%    | 58.4%  | 64.8%            | 70.8%                   |

With the more expensive hydrogen storage now 83 instead of 77 SPS are required to completely cover the power demand only with SPS. This 8% higher number corresponds to 1838 GW<sub>p</sub> in space and

additional 238 GW<sub>p</sub> on ground. The optimized storage capacity accounts to 9069 GWh in the form of hydrogen, which yields released to electric power 4988 GWh of electricity. The necessary power for charge/discharge the system is increased to 420 GW<sub>el</sub> but storage usage decreased to 49 TWh<sub>el</sub>. With higher installation numbers of the generation system the dumped electricity increases more than 40%. As result, this configuration accounts for levelised electricity costs of slightly below 10 Cent/kWh, where now below 60% pertain to power generation and over 25% to storage and dumping.

The low storage efficiency in combination with the therefore high storage costs shows a significantly higher impact on the configuration of a pure terrestrial power supply. Usage of storage is slightly reduced by 4% to 2309 TWh<sub>el</sub> but nevertheless a tremendously higher amount of PV peak power has to be installed in spite: 4844 GW<sub>p</sub> are necessary to generate the also 185% augmented total generated electricity of 10561 TWh<sub>el</sub>. A large portion of it is necessary to cover the higher losses of the storage system, further 1870 TWh<sub>el</sub> were dumped. For storing hydrogen, a capacity of 19503 GWh<sub>H<sub>2</sub></sub> corresponding to an electric capacity of 10727 GWh<sub>el</sub> is needed. The LEC finally rises to nearly 11 Cent/kWh with hydrogen storage and is therefore higher than for the space system. Storage and dumping thus account for over 70% of the costs whereas for generation less than 20% and 16% for transmission is identified. Again, the capacities and yields of different combination shares are lying between these values. The data of Table 80 are graphically illustrated in Figure 77, Figure 78 as well as Figure 81 and Figure 82.

As in S-1 additional calculations were performed with 5 respectively 10 times higher transportation costs. Thus the LEC goes up again tremendously to 30 Cent/kWh for transportation costs of 2650 €/kg respectively 55 Cent/kWh for 5300 €/kg for the case of pure power supply by SPS. Detailed results are presented in Table 81 and Table 82.

Table 81. Calculations for combined scenario 2 with 5 times higher transportation costs: 2650 €/kg

| Combination level      | SPS only | ...   | combined | ...   | terrestrial only |             |
|------------------------|----------|-------|----------|-------|------------------|-------------|
| Number of SPS          | 82       | 60    | 45       | 30    | 15               | 0           |
| Terr. generation ratio | 0%       | 36.7% | 58.4%    | 75.5% | 89.1%            | 100%        |
| <b>Resulting LEC</b>   |          |       |          |       |                  |             |
| Interest rate 6%       | 0.301    | 0.256 | 0.227    | 0.195 | 0.159            | 0.108 €/kWh |
| <b>LEC Breakdown</b>   |          |       |          |       |                  |             |
| Generation             | 65.4%    | 54.5% | 45.2%    | 37.2% | 29.4%            | 18.5%       |
| SPS                    | 64.5%    | 50.6% | 39.1%    | 28.7% | 17.5%            | 0%          |
| SPS-PV                 | 0.9%     | 0.5%  | 0.4%     | 0.2%  | 0.1%             | 0%          |
| Terrestrial PV         | 0%       | 3.4%  | 5.7%     | 8.4%  | 11.7%            | 18.5%       |
| Transmission           | 12.0%    | 10.9% | 10.0%    | 9.6%  | 9.5%             | 10.7%       |
| Storage and dumping    | 22.6%    | 34.6% | 44.8%    | 53.2% | 61.1%            | 70.8%       |

Table 82. Calculations for combined scenario 2 with 10 times higher transportation costs: 5300 €/kg

| Combination level      | SPS only | ...   | combined | ...   | terrestrial only |             |
|------------------------|----------|-------|----------|-------|------------------|-------------|
| Number of SPS          | 82       | 60    | 45       | 30    | 15               | 0           |
| Terr. generation ratio | 0%       | 36.7% | 58.4%    | 75.4% | 89.1%            | 100%        |
| <b>Resulting LEC</b>   |          |       |          |       |                  |             |
| Interest rate 6%       | 0,554    | 0.450 | 0.379    | 0.303 | 0.219            | 0.108 €/kWh |
| <b>LEC Breakdown</b>   |          |       |          |       |                  |             |
| Generation             | 66.8%    | 56.7% | 48.0%    | 40.4% | 32.5%            | 18.5%       |
| SPS                    | 66.4%    | 54.5% | 44.4%    | 34.9% | 24.0%            | 0%          |
| SPS-PV                 | 0.5%     | 0.3%  | 0.2%     | 0.2%  | 0.1%             | 0%          |
| Terrestrial PV         | 0%       | 1.9%  | 3.4%     | 5.4%  | 8.5%             | 18.5%       |
| Transmission           | 11.4%    | 10.2% | 9.2%     | 8.7%  | 8.7%             | 10.7%       |
| Storage and dumping    | 21.8%    | 33.1% | 42.8%    | 50.9% | 58.8%            | 70.8%       |

Compared to scenario S-1, the hydrogen storage rises the levelised electricity costs by 6 to 7% on the side of SPS only but by 66% for a terrestrial solar power supply by photovoltaic, showing on the latter a tremendously higher impact. Another time no advantage of a combination of SPS and terrestrial PV systems results. On contrary, for transportation costs of 530 €/kg the LEC of the combined scenarios shows a maximum at a portion of 95% terrestrial and 5% space supply, voting for a pure SPS (or terrestrial) solution. The variation of the LEC within 1.3 Cent/kWh is small though and falls from its maximum value of 11.1 Cent/kWh to 10.8 Cent/kWh for pure terrestrial and to 9.8 Cent/kWh for pure SPS as most favourable solution of S-2. However, as the assumptions are based on estimations with far higher insecurities, deviations of the real LEC to the calculated one due to a different cost development may probably be higher than this variation, in whatever direction. Over all, high storage costs favour SPS.

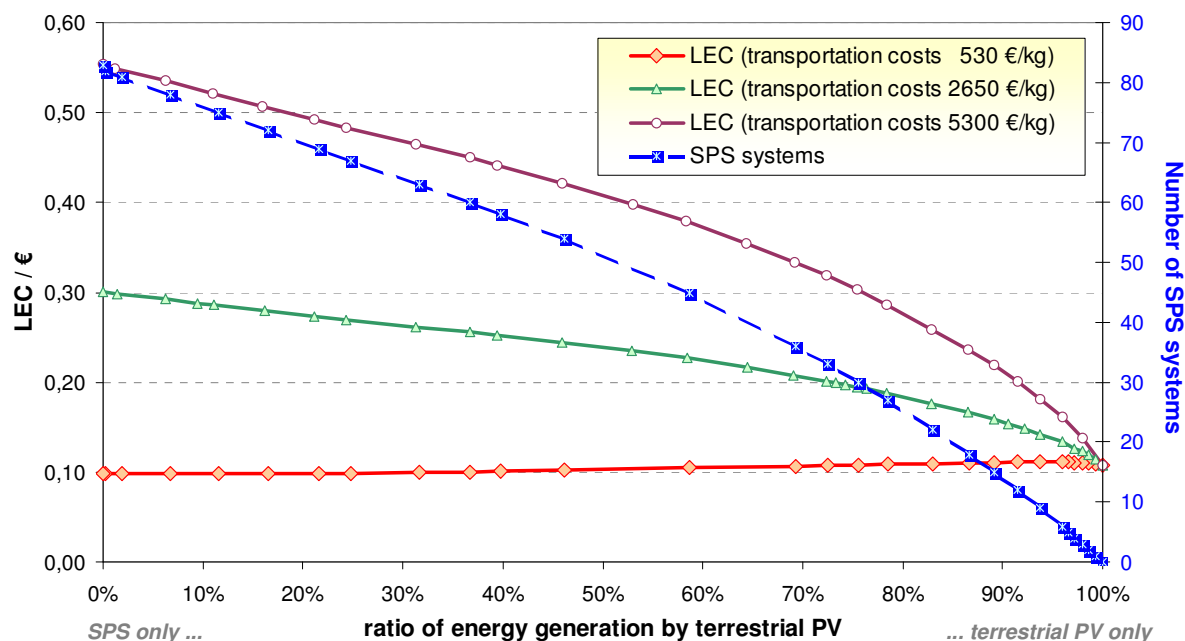


Figure 77. LEC of combined scenario 2 in dependence on the ratio of SPS- and terrestrial PV energy generation for several transportation costs

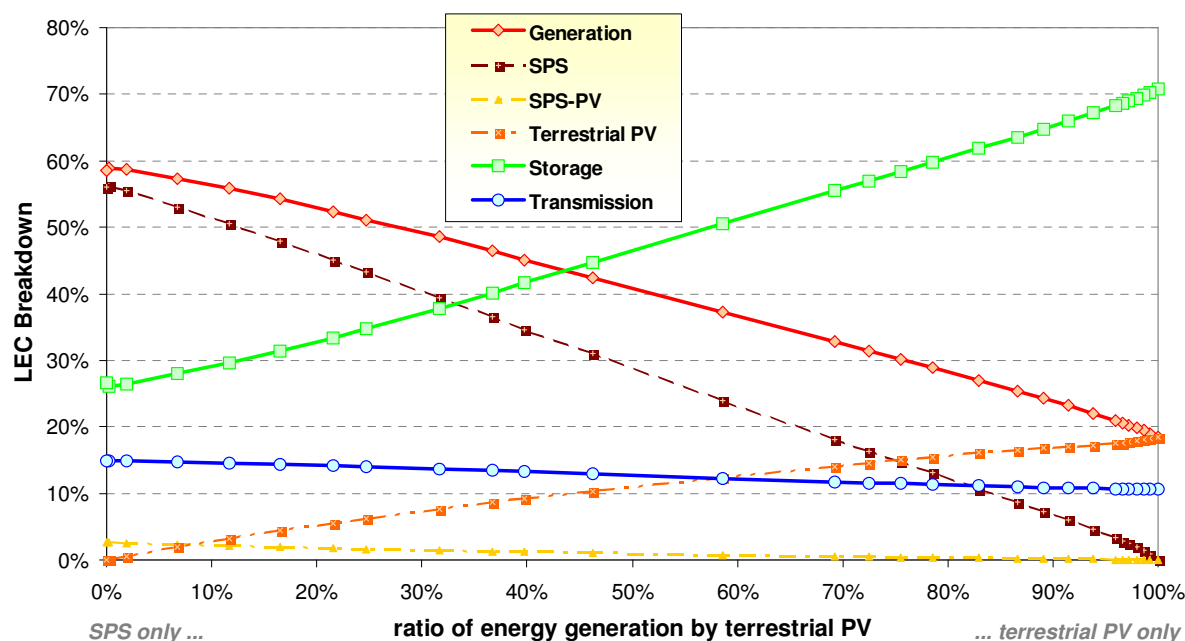


Figure 78. LEC breakdown of combined scenario 2 in dependence on the ratio of SPS- and terrestrial PV energy generation with launch costs of 530 €/kg

At the breakdown of the levelised electricity costs the higher amount of the storage and dumping costs can be seen. For space transportation costs of 530 €/kg they show a portion of 27% for pure SPS, rising up to over 70% for pure terrestrial. For higher space transportation costs it is just starting from values of about 22%.

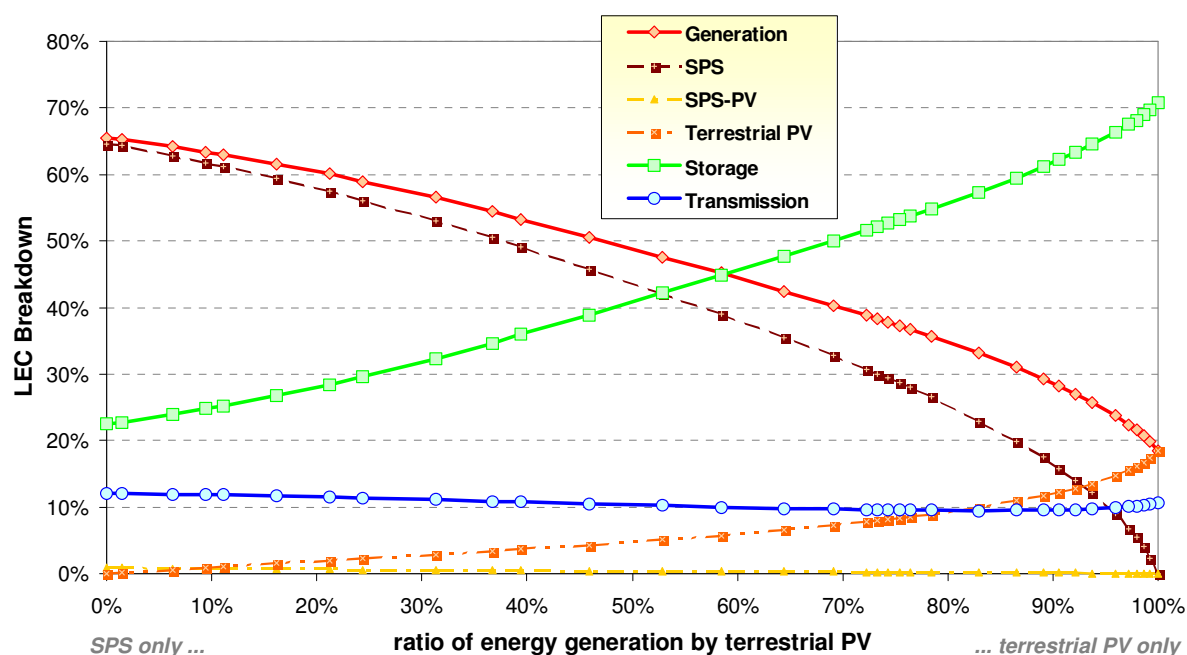


Figure 79. LEC breakdown of combined scenario 2 in dependence on the ratio of SPS- and terrestrial PV energy generation with launch costs of 2650 €/kg

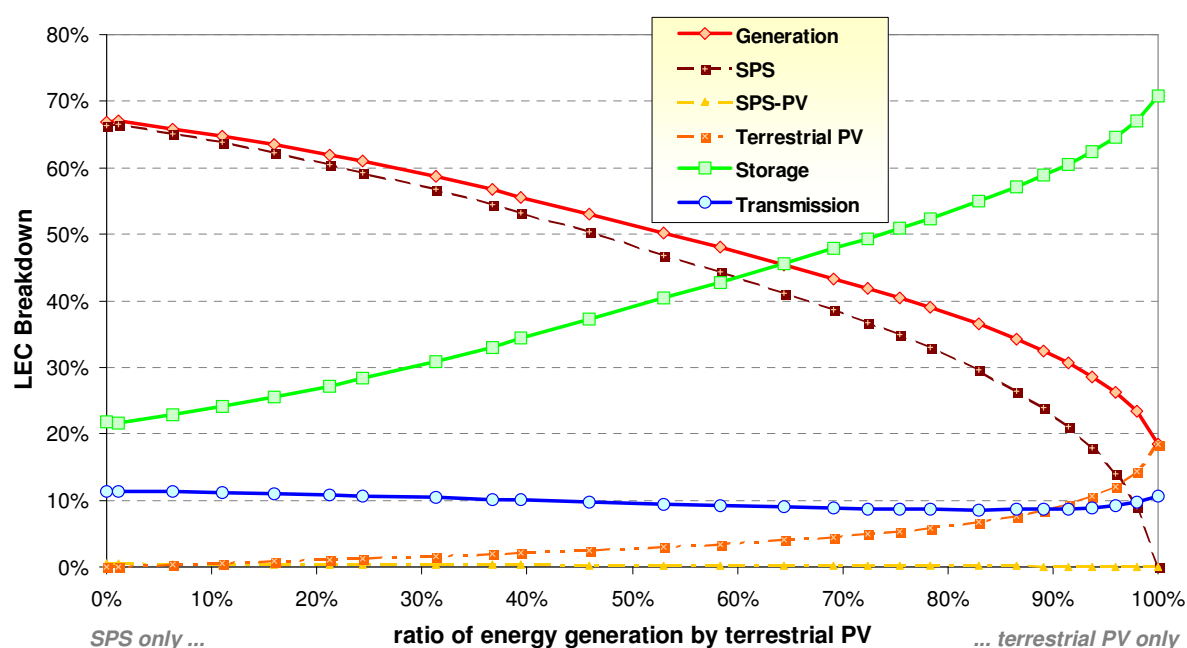


Figure 80. LEC breakdown of combined scenario 2 in dependence on the ratio of SPS- and terrestrial PV energy generation with launch costs of 5300 €/kg

In Figure 81 the required power capacities are plotted. The significantly higher power installations of the terrestrial PV system and the storage can obviously be noted. In S-2 they show no more a linear but potential rise.

Figure 82 presents the generated annual energy amounts split into the three generation systems, the dumped energy amount, storage usage as well as the storage capacities (right side axis) in GWh in equivalents of hydrogen respectively re-converted to electricity. The storage usage is here



considerably lower for a high space share than in S-1 but increasing significantly in direction to higher terrestrial shares. The dumped energy amount is also remarkably rising for higher terrestrial shares.

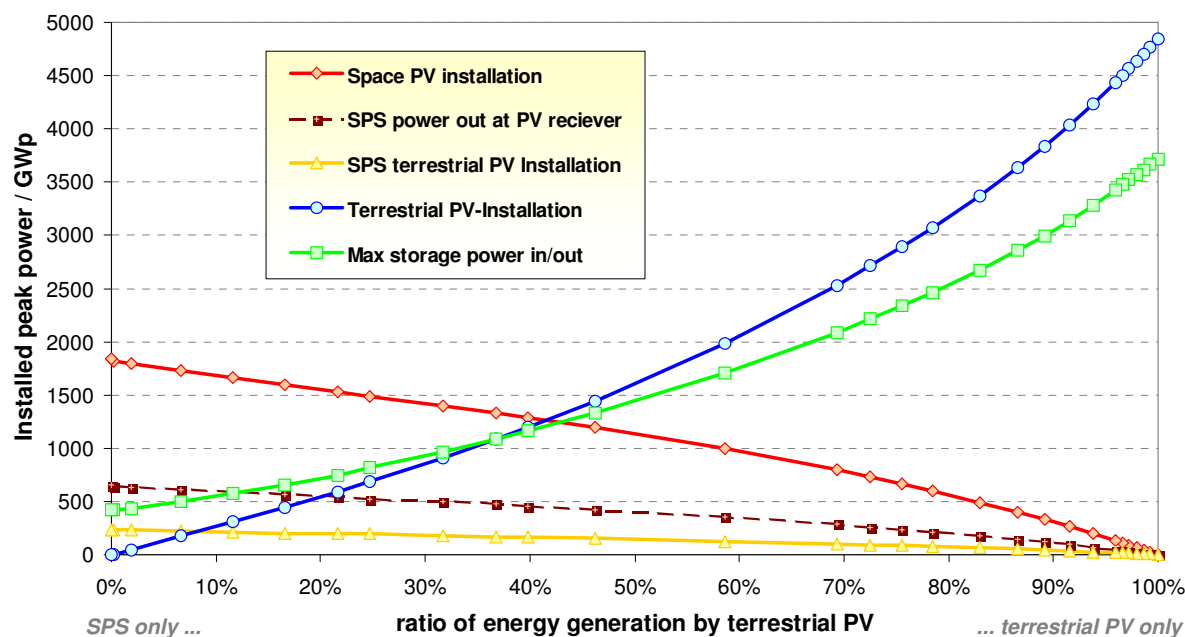


Figure 81. Installed power capacities and maximal power from the SPS ground receiver and power into or out of storage in dependence on the ratio of SPS- and terrestrial PV energy generation for combined scenario 2

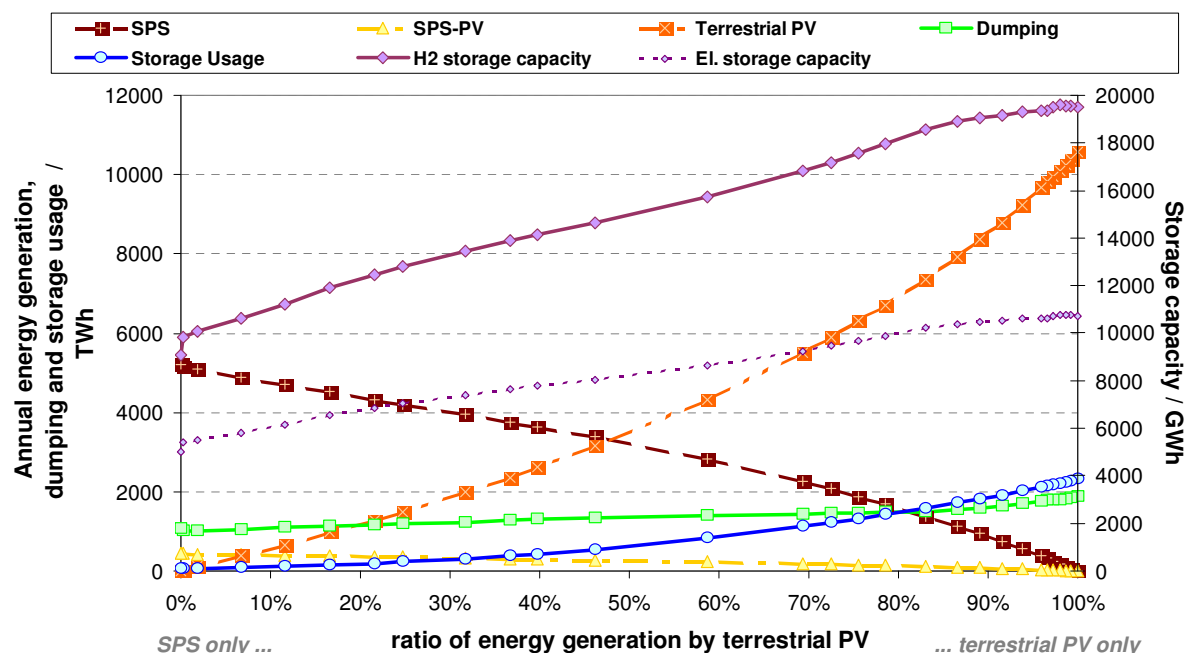


Figure 82. Annual sums of generated energy split for all of the three sources as well as dumped energy, storage usage and the storage capacity in dependence on the ratio of SPS and terrestrial PV for the combined scenario 1

### 5.4 Scenario 3: SPS-optimized Ground PV

Within scenario 3, pumped hydroelectric storage was chosen as in S-1 but the complete PV installed on earth was optimized for capturing the SPS laser beam:  $32^\circ$  inclined to the south, perpendicular to the direction to the geo-stationary power satellite and with a distance between the rows adjusted to prevent losses of the laser beam. This configuration lowers possible annual amounts of the terrestrial irradiation but has the advantage that the location on earth where to send the laser beam can be freely chosen within the installed capacity, therefore maximizing the SPS gain (on costs of terrestrial gains). However, in contrary to the S-1 scenario, PV on ground (including SPS receiver and the terrestrial PV) here was assumed equally spread over the whole generation zone A3 with the maximal necessary amount of PV installed. Thus at small proportions of SPS the cloudless sites will be selected to serve as SPS ground receiver. At higher SPS proportions subsequently also non-optimal sites have to be used as ground receiver. At pure SPS no choice of the receiver site is possible, taking the average of irradiation and cloudiness of generation zone A3 for the output calculations. The results of the calculations for scenario S-3 for transportation costs of 530 €/kg are shown in Table 83.

Table 83. Calculations of the combined scenario 3, transportation costs: 530 €/kg

| Combination level      | SPS only | ...   | combined | ...   | terrestrial only |                      |
|------------------------|----------|-------|----------|-------|------------------|----------------------|
| <b>Number of SPS</b>   | 78       | 60    | 45       | 30    | 15               | 0                    |
| Space PV installation  | 1727     | 1328  | 996      | 664   | 332              | 0 GW <sub>p</sub>    |
| Max SPS ground out     | 613      | 471   | 353      | 236   | 118              | 0 GW <sub>p</sub>    |
| SPS generation         | 4813     | 3768  | 2867     | 1939  | 983              | 0 TWh                |
| SPS generation ratio   | 92.2%    | 69.7% | 49.6%    | 31.6% | 15.2%            | 0%                   |
| <b>SPS-PV receiver</b> |          |       |          |       |                  |                      |
| PV installation        | 221      | 170   | 127      | 85    | 42               | 0 GW <sub>p</sub>    |
| Generation             | 408      | 319   | 243      | 164   | 83               | 0 TWh                |
| SPS-PV gen. Ratio      | 7.8%     | 5.9%  | 4.2%     | 2.7%  | 1.3%             | 0%                   |
| <b>Terrestrial PV</b>  |          |       |          |       |                  |                      |
| PV installation        | 0        | 676   | 1366     | 2064  | 2756             | 3478 GW <sub>p</sub> |
| Generation             | 0        | 1322  | 2673     | 4037  | 5392             | 6804 TWh             |
| Terr. Generation ratio | 0%       | 24.4% | 46.2%    | 65.8% | 83.5%            | 100%                 |
| <b>Storage</b>         |          |       |          |       |                  |                      |
| Pumped Hydro           | 374      | 734   | 1176     | 1636  | 2092             | 2576 GW              |
| Storage Capacity       | 15434    | 13217 | 8507     | 8807  | 11236            | 13549 GWh            |
| Storage usage          | 105      | 379   | 815      | 1320  | 1855             | 2413 TWh             |
| Total generation       | 5221     | 5409  | 5783     | 6139  | 6457             | 6804 TWh             |
| Dumping                | 736      | 880   | 1172     | 1434  | 1653             | 1897 TWh             |
| <b>Resulting LEC</b>   |          |       |          |       |                  |                      |
| Interest rate 6%       | 0.095    | 0.091 | 0.089    | 0.086 | 0.084            | 0.077 €/kWh          |
| <b>LEC Breakdown</b>   |          |       |          |       |                  |                      |
| Generation             | 63.7%    | 58.0% | 50.6%    | 43.0% | 36.0%            | 27.2%                |
| SPS                    | 60.8%    | 48.5% | 36.0%    | 24.5% | 13.6%            | 0%                   |
| SPS-PV                 | 2.8%     | 1.8%  | 1.2%     | 0.7%  | 0.3%             | 0%                   |
| Terrestrial PV         | 0%       | 7.7%  | 13.4%    | 17.9% | 22.0%            | 27.2%                |
| Transmission           | 15.8%    | 15.6% | 15.0%    | 14.5% | 14.2%            | 14.2%                |
| Storage and dumping    | 20.6%    | 26.4% | 34.4%    | 42.4% | 49.9%            | 58.6%                |

For pure terrestrial power supply here 3478 GW<sub>p</sub> are needed, which is about 1/3 more than in scenario S-1, to produce 6804 TWh. This is an increase of 20%. The storage capacity has to be augmented by 8% to 13549 GWh with a 40% higher input/output power. Storage usage stays nearly the same, hence compared to S-1 the 2.3-fold amount of energy is dumped. Finally this results in 20% higher levelised electricity costs of 7.7 Cents/kWh. Thus the LEC breakdown shows a lower portion for generation and a raised portion of nearly 60% for storage and dumping.

Towards full power supply with pure SPS the LEC is continuously increasing to 9.5 Cents per kWh. 78 SPS systems are necessary, accounting for 1727 GW<sub>p</sub> in space and 221 GW<sub>p</sub> as ground receiver, generating with 5221 TWh annually about the same amount as in S-1. The costs here are 3% above that of S-1 because of the spread of the ground receiver over the whole generation zone A3. Placing them in the regions with lowest probability of clouds would lead to the same values as in S-1 for pure

SPS, approaching that value for combined systems. Thus the different configuration of the equal spread within S-3 scenario gives additional information on the impact of deviating control and regulation mechanisms of the laser beam on the costs.

The numbers of capacities, power levels and costs of the combined systems are somewhere in between. They are listed in Table 83 and graphically illustrated in Figure 83 to Figure 86. Again, no advantage of a combination of space and terrestrial systems can be stated, neither for spreading the ground receiver equally over the whole generation zone A3 nor for placing them at most promising sites.

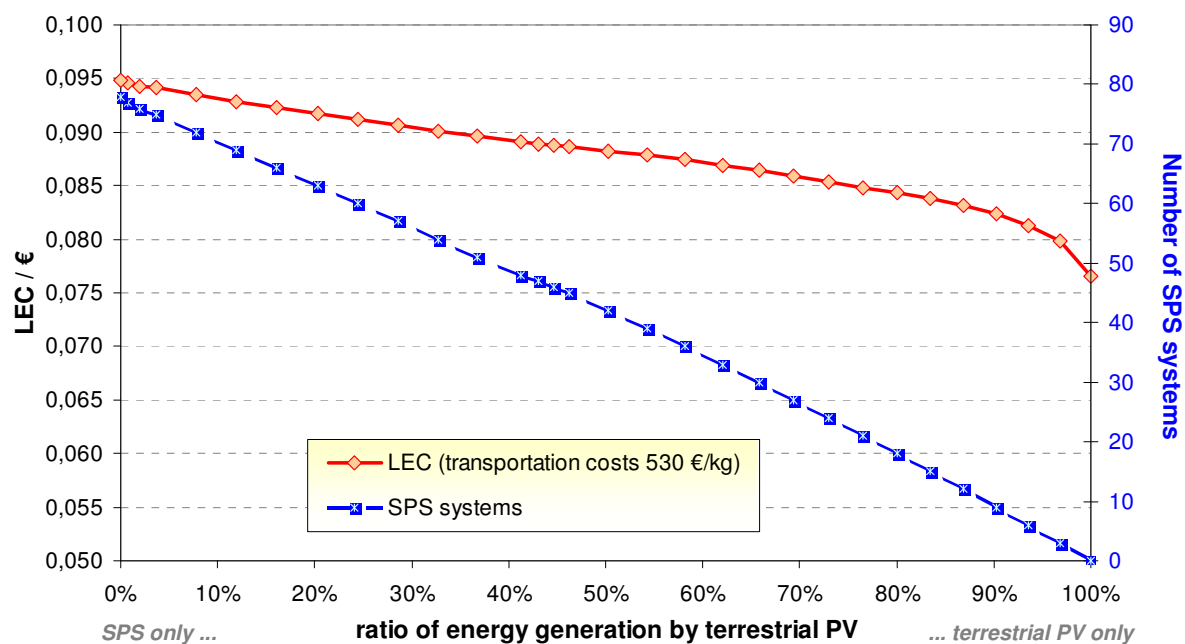


Figure 83. LEC of combined scenario 3 in dependence on the ratio of SPS- and terrestrial PV energy generation for transportation costs of 530 €/kg

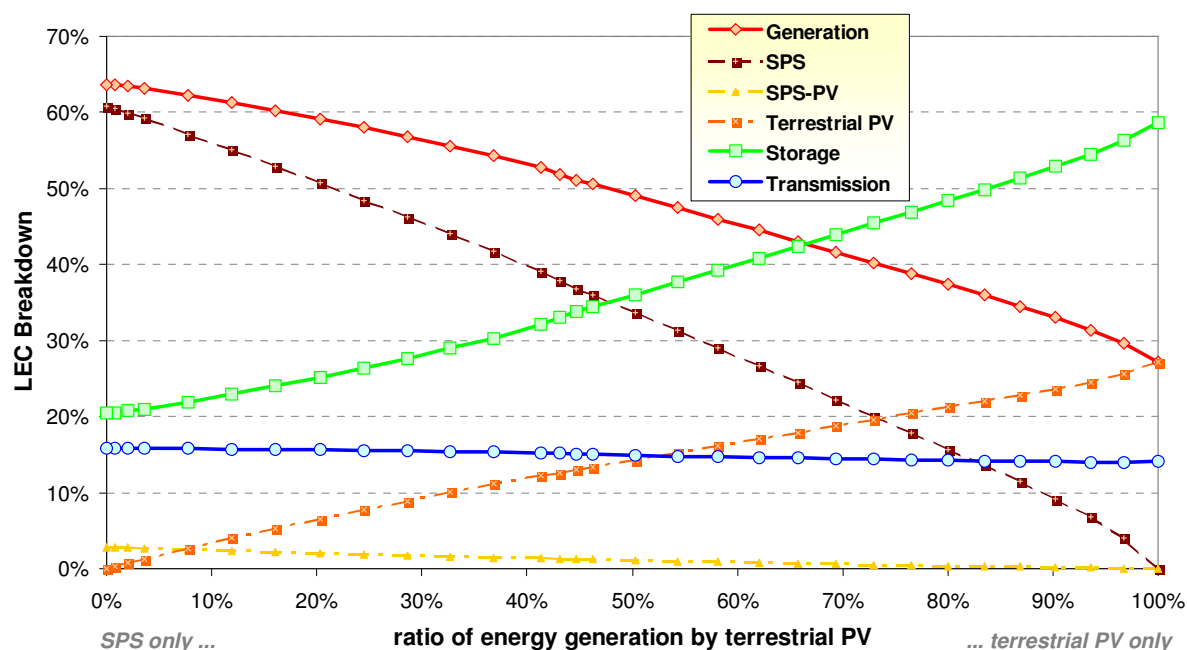


Figure 84. LEC breakdown of combined scenario 3 in dependence on the ratio of SPS- and terrestrial PV energy generation with launch costs of 530 €/kg

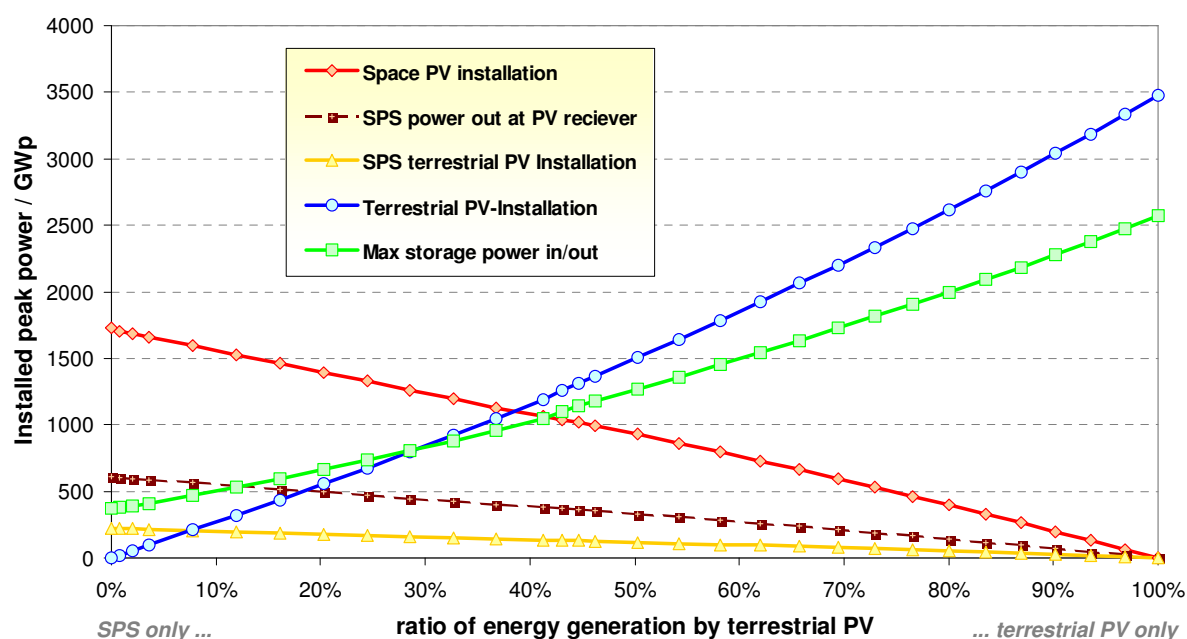


Figure 85. Installed power capacities and maximal power from the SPS ground receiver and power into or out of storage in dependence on the ratio of SPS- and terrestrial PV energy generation for combined scenario 3

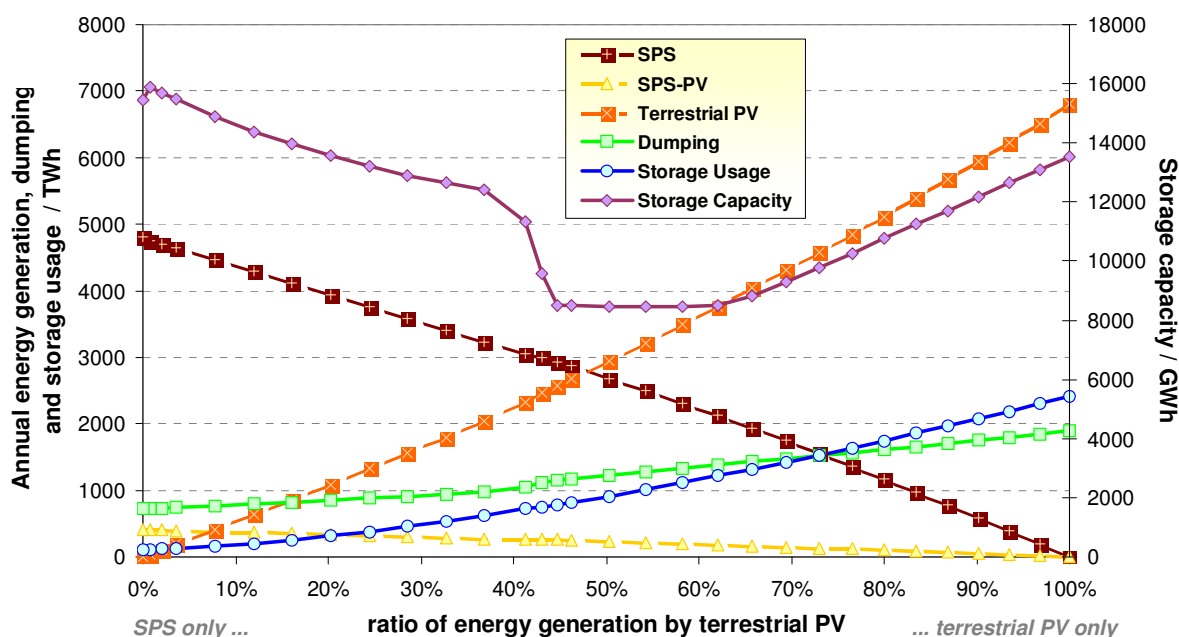


Figure 86. Annual sums of generated energy split for all of the three sources as well as dumped energy, storage usage and the storage capacity in dependence on the ratio of SPS and terrestrial PV for the combined scenario 3

In contrary to the previous scenarios, the course of the cost optimised storage capacities in Figure 86 shows a minimum at combined space-terrestrial solutions, increasing to both sides. As will be outlined in paragraph 5.6, the storage and terrestrial PV capacities can be adapted within a broad range in order to get the lowest LEC.

## 5.5 Scenario 4: Solar optimised ground PV

In the fourth scenario the whole PV on the ground including the ground receiver as well as the terrestrial PV was optimised for collecting solar and daylight irradiation on ground. Background was the idea of primarily starting with terrestrial PV installation and a later add on of the space technology to a yet existing terrestrial PV plant. Thus the installation of the primarily terrestrial PV plant is assumed optimised for ground use.

On ground shading of the elements at low solar angles has to be respected. Figure 87 shows the losses of the annual generated energy of PV modules facing south and inclined  $10^\circ$  in summer and  $60^\circ$  in winter in dependence on the row distance. The row distance is presented in units of the module width and was determined in hourly calculations. At small row distances below 1.6 units the annual gain is decreasing strongly. With increasing row distance the losses are converging to zero. Finally as rough estimation a row distance of 1.8 module units was selected to keep the losses below 0.5%.

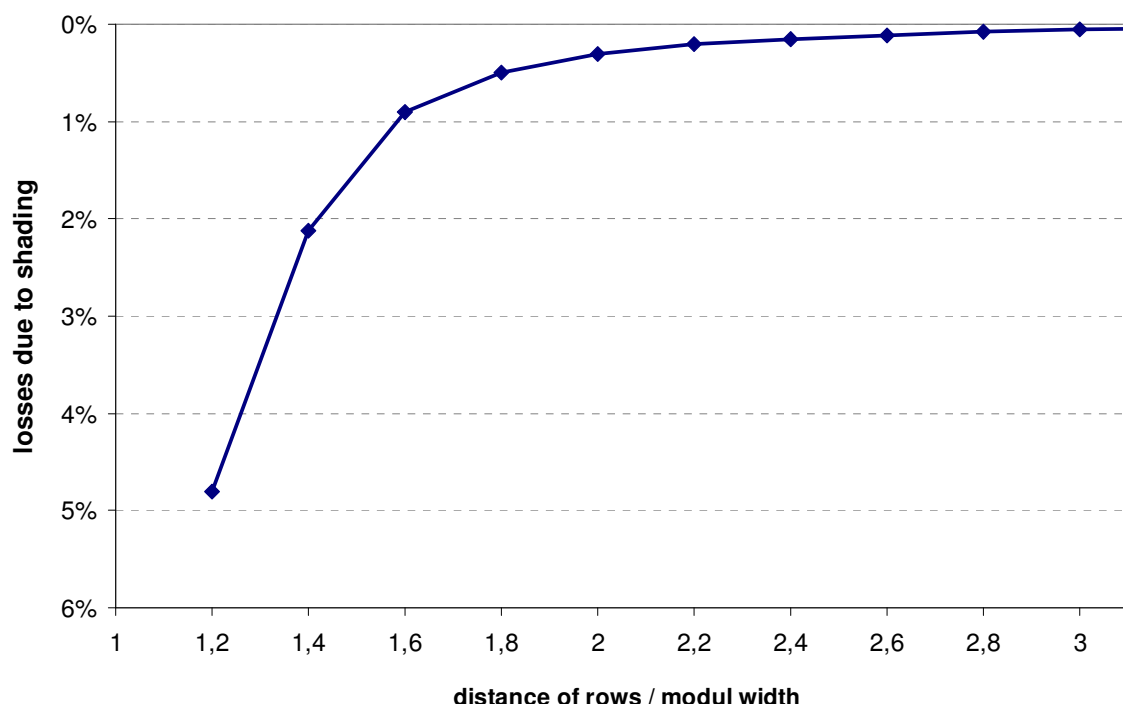


Figure 87. Decrease of the annual sum of a 1 GW PV array due to shading losses in dependence on the row distance (in units of the module width)

Table 84 shows the results for scenario S-4. With that high row distance of 1.8 times the module widths, 62% of the laser beam in winter and 34% in summer hits the ground instead of the PV module. This requires the installation of 205 SPS to cover the energy demand completely by the space system, which is more than two and half times the necessary amount as when the ground receiver is adapted for the laser beam. From the installed 4539 GW<sub>p</sub> in space remain during summer maximal 1071 GW<sub>p</sub>, during winter only 611 GW<sub>p</sub> instead of 1500 GW<sub>p</sub> at laser beam optimised ground PV. Within the whole year the 205 SPS deliver only 6871 TWh plus 742 TWh from the 376 GW<sub>p</sub> of the corresponding ground receiver. The storage capacity accounts to 6933 GWh with a power of 859 GW. Whereas only 76 TWh are used for storage, 3101 TWh are dumped – more than 3 to 4 times the amount as compared to the laser-optimised receiver. The levelised electricity costs for one kWh then mount up to 19.2 Cents with 10% for transmission and the remaining 90% nearly equally for generation respectively dumping and storage. With an increasing share of terrestrial PV the LEC is continuously decreasing to 6.6 Cent/kWh like in the optimised scenario S-1. An installation of 2706 GW<sub>p</sub> of PV is required for pure terrestrial power supply, delivering annually 5870 TWh with a storage capacity of 12185 GWh and a maximal input/output power of 1900 GW. Then 2403 TWh are used at storage and only 976 TWh have to be dumped. The numbers are slightly deviating to those of S-1 because of a slightly different modeling of the optimised collocation of the PV and due to the solver exactness. The cost breakdown shows an increase of storage and dumping costs to 50%, transmission to 16% whereas the proportion for generation decreases to 34%.

Table 84. Calculations for the combined scenario 4 for transportation costs of 530 €/kg

| Combination level      | SPS only | ...   | combined | ...   | terrestrial only |                      |
|------------------------|----------|-------|----------|-------|------------------|----------------------|
| <b>Number of SPS</b>   | 205      | 164   | 123      | 82    | 41               | 0                    |
| Space PV installation  | 4539     | 3631  | 2723     | 1815  | 908              | 0 GW <sub>p</sub>    |
| Max SPS ground out     | 1071     | 856   | 642      | 428   | 214              | 0 GW <sub>p</sub>    |
| SPS generation         | 6871     | 5581  | 4249     | 2876  | 1459             | 0 TWh                |
| SPS generation ratio   | 90.3%    | 78.3% | 63.3%    | 45.0% | 23.8%            | 0%                   |
| <b>SPS-PV receiver</b> |          |       |          |       |                  |                      |
| PV installation        | 376      | 299   | 223      | 152   | 76               | 0 GW <sub>p</sub>    |
| Generation             | 742      | 599   | 452      | 312   | 158              | 0 TWh                |
| SPS-PV gen. ratio      | 9.7%     | 8.4%  | 6.7%     | 4.9%  | 2.6%             | 0%                   |
| <b>Terrestrial PV</b>  |          |       |          |       |                  |                      |
| PV installation        | 0        | 435   | 929      | 1473  | 2081             | 2706 GW <sub>p</sub> |
| Generation             | 0        | 944   | 2015     | 3196  | 4513             | 5870 TWh             |
| Terr. generation ratio | 0%       | 13.3% | 30.0%    | 50.1% | 73.6%            | 100%                 |
| <b>Storage</b>         |          |       |          |       |                  |                      |
| Pumped Hydro           | 859      | 948   | 1113     | 1332  | 1612             | 1900 GW              |
| Storage Capacity       | 6933     | 7623  | 8644     | 9662  | 10603            | 12185 GWh            |
| Storage usage          | 76       | 202   | 406      | 808   | 1569             | 2403 TWh             |
| Total generation       | 7613     | 7124  | 6716     | 6384  | 6130             | 5870 TWh             |
| Dumping                | 3101     | 2597  | 2160     | 1766  | 1381             | 976 TWh              |
| <b>Resulting LEC</b>   |          |       |          |       |                  |                      |
| Interest rate 6%       | 0.192    | 0.169 | 0.147    | 0.124 | 0.099            | 0.066 €/kWh          |
| <b>LEC Breakdown</b>   |          |       |          |       |                  |                      |
| Generation             | 46.1%    | 48.3% | 49.4%    | 48.9% | 45.4%            | 33.8%                |
| SPS                    | 44.9%    | 45.5% | 44.1%    | 39.6% | 29.0%            | 0%                   |
| SPS-PV                 | 1.2%     | 1.1%  | 1.0%     | 0.8%  | 0.6%             | 0%                   |
| Terrestrial PV         | 0%       | 1.7%  | 4.3%     | 8.5%  | 15.9%            | 33.8%                |
| Transmission           | 10.3%    | 11.1% | 11.9%    | 12.8% | 13.8%            | 15.9%                |
| Storage and dumping    | 43.6%    | 40.6% | 38.7%    | 38.3% | 40.8%            | 50.3%                |

The numbers of Table 84 are graphically illustrated as like for the other scenarios in Figure 88 to Figure 91 in dependence on the combination share. Whereas the LEC decreases more or less linearly with higher terrestrial shares, the breakdown of the LEC shows an increase of its total generation share for combined levels and the storage share a minimum within the same range.

The so dramatically increasing LEC for higher SPS shares excludes scenario 4. This is obvious because high amounts of the expensive laser energy from space are not used within the gaps between single the PV rows. In reality primarily installed terrestrial PV for sure will be changed for the option of serving as a SPS laser beam receiver in that way, that the gaps will be filled by further PV panels to use the whole laser beam.



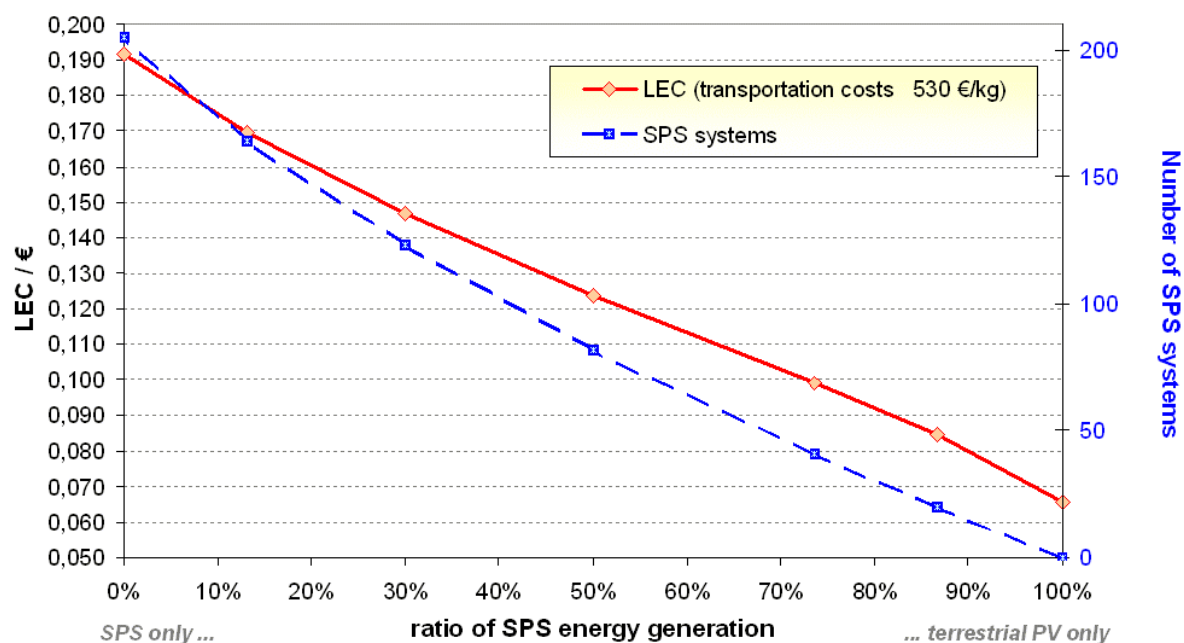


Figure 88. LEC of combined scenario 4 in dependence on the ratio of SPS- and terrestrial PV energy generation for transportation costs of 530 €/kg

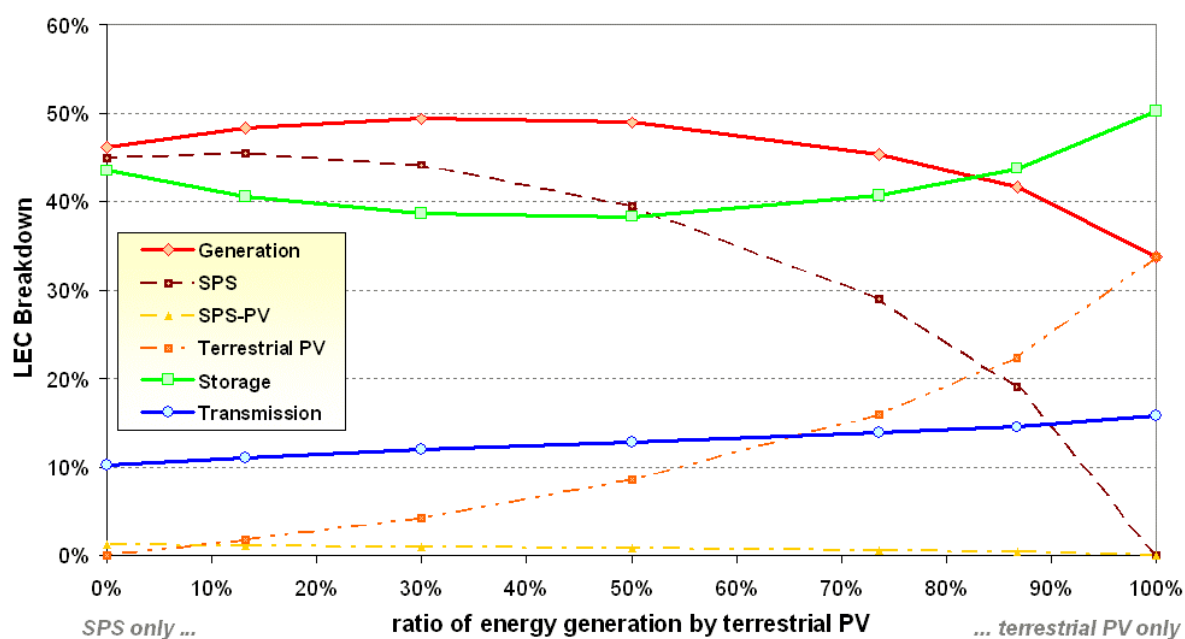


Figure 89. LEC breakdown of combined scenario 4 in dependence on the ratio of SPS- and terrestrial PV energy generation with launch costs of 530 €/kg

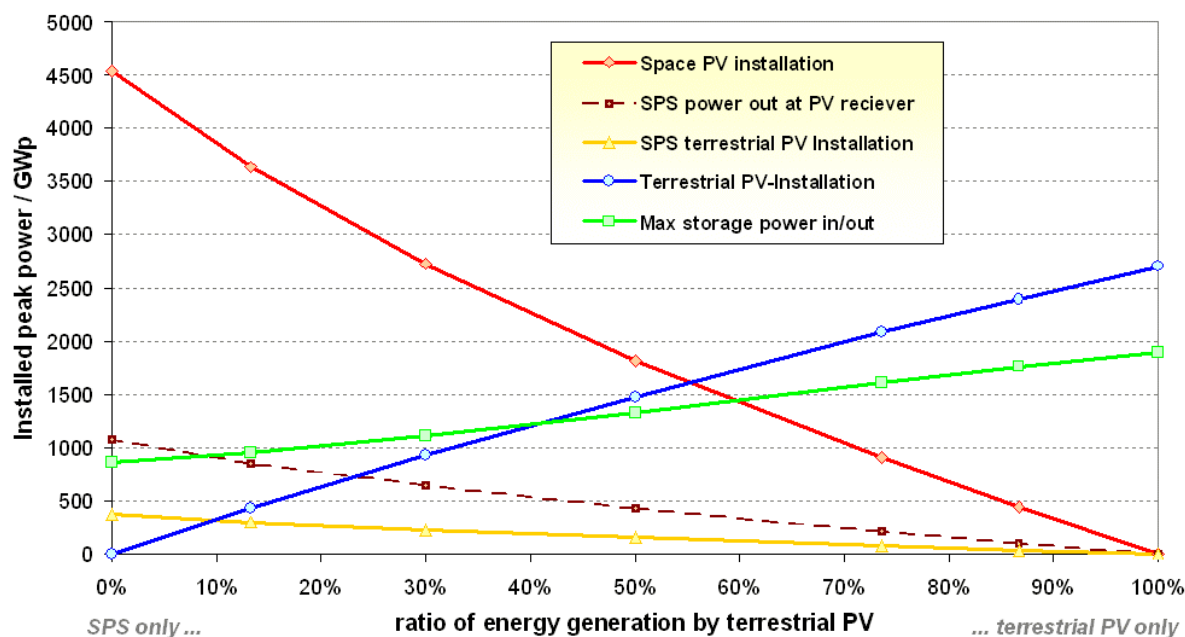


Figure 90. Installed power capacities and maximal power from the SPS ground receiver and power into or out of storage in dependence on the ratio of SPS- and terrestrial PV energy generation for combined scenario 4

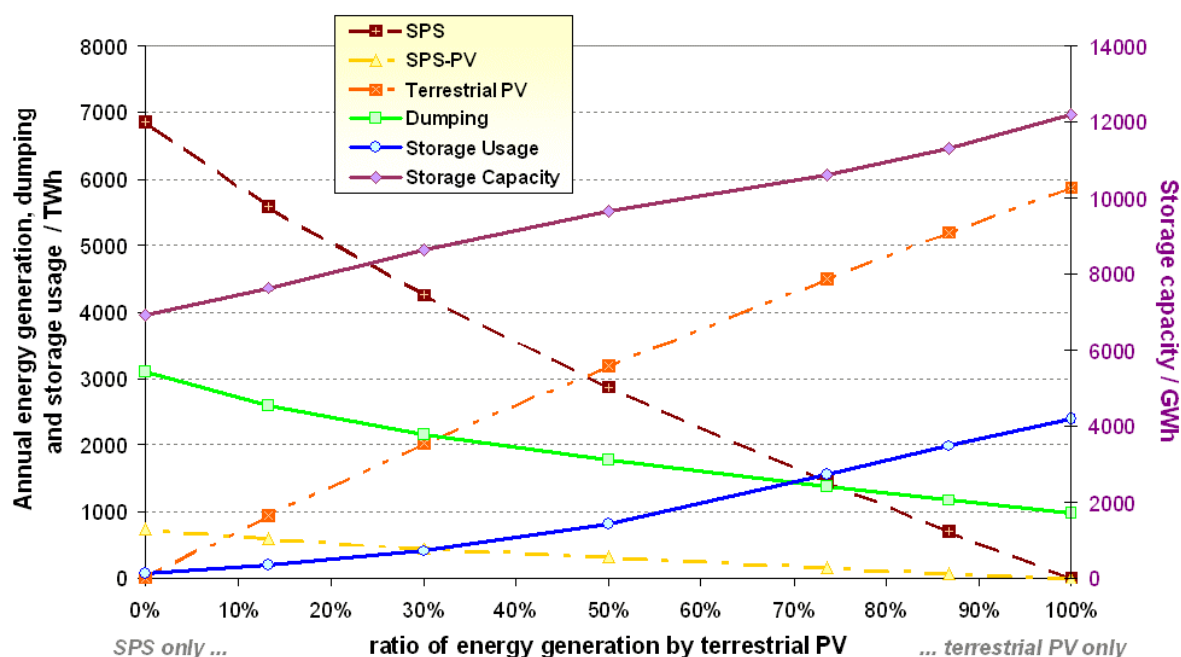


Figure 91. Annual sums of generated energy split for all of the three sources as well as dumped energy, storage usage and the storage capacity in dependence on the ratio of SPS and terrestrial PV for the combined scenario 4

## 5.6 Variation of storage and generation capacities

With a higher installation capacity of power generating PV systems, the storage capacity can be reduced as it is replaced by the generation system and vice versa. Thus, generation and storage system

are dependent on each other and to a certain amount mutually exchangeable among each other. The optimised numbers were selected according to the lowest levelised electricity costs and are therefore dependent on the prices of both systems. To get an impression on the dependency of both dimensions on each other, the LEC and the necessary PV capacity was calculated in dependence on the storage capacity. The results are presented in Figure 92 for scenarios S-1 (lower lines) and S-2 (upper lines): LEC as full lines and the corresponding PV capacity as dashed lines.

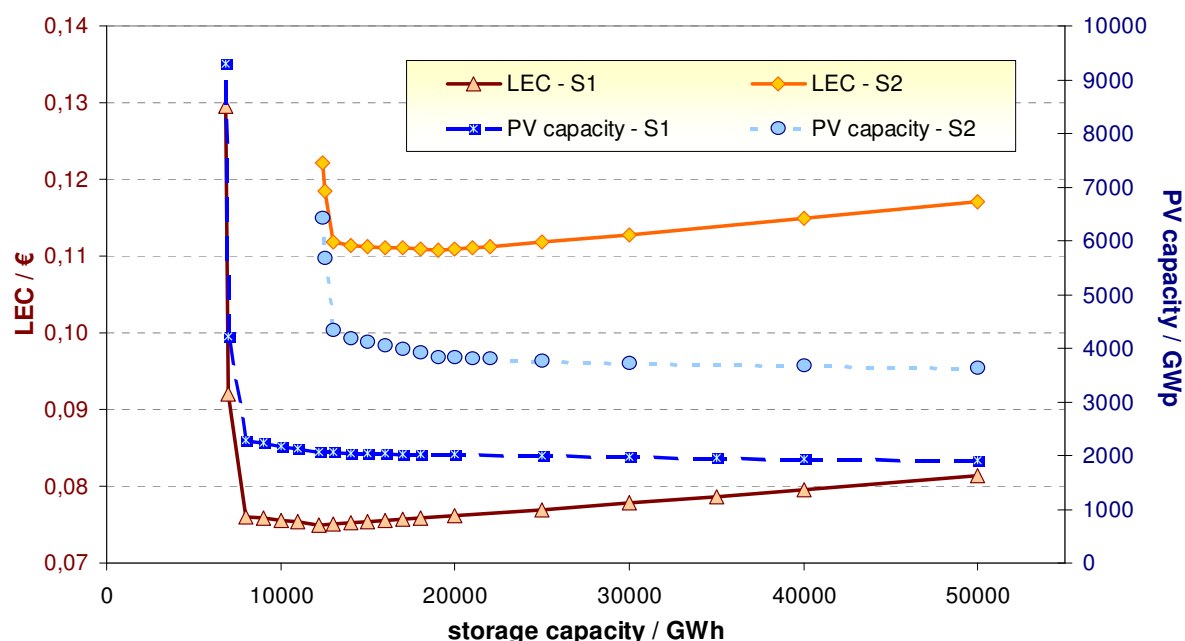


Figure 92. LEC for several variations of the storage capacity within scenarios 1 and 2 exemplarily for a combination of 15 SPS with terrestrial PV

Coming from high storage capacities, the PV capacity stays primarily on the same level, then slightly augmenting until it rises abruptly at a certain value, which is depending on the scenario. The LEC on contrary is primarily slightly descending to a broad minimum, then slightly increasing until a similar abrupt rise at the same storage capacity. For the understanding of the curves it is important to recall that the price of the storage system consists of two portions: the price of the storage capacity and that of the electricity/storage conversion system, depending on its power level. The latter of course is strongly connected to the power generation system and far more expensive than the storage capacity. For sufficient energy generation a certain minimal amount of PV capacity is required, represented by the PV capacity at high storage capacity levels. This storage capacity is completely oversized but allows the power level of the energy conversion system to be small. The increase of the LEC here accounts only on the storage capacity.

Approaching the optimal LEC value lowering the storage capacity, the costs for the storage capacity is decreasing but slightly higher generation respectively energy conversion power levels are necessary, compensating finally the lower storage capacity costs.

At the point of the abrupt rise of the LEC and the PV capacity, the storage capacity comes to a point where it is too small. To some amount it can be replaced by significantly higher PV capacities, hence rising also the LEC because of the high price of the generation system. Under a certain level the lacking storage capacity cannot be compensated by higher generation system amount.

Finally, the efficiency of the storage system determines the minimal required generation capacity as well as the minimal storage capacity, its price determines the LEC. When the generation and storage

system are designed with at least its minimal capacities, a further optimization does not show a strong impact with the prices as assumed herein. This characteristic is the same for both, the cheaper and the expensive storage systems.

## 5.7 Summary of LEC for the combined scenario

For better comparison purposes, the LEC of the four investigated combined scenarios are plotted together within one graph in Figure 93. Solar power supply by SPS and/or terrestrial systems can be achieved at a price lower than 10 Cents/kWh depending on the storage system and the PV configuration on ground. The need of adapting the ground receiver to the laser beam can be detected obviously by the strongly increasing LEC for scenario 4 for higher space shares. However, no advantages of the combination of space and terrestrial power systems can be deduced from the calculations within this study. For optimised systems and a pumped hydroelectric storage system the configuration showing the lowest levelised electricity costs is a pure terrestrial configuration. With the less efficient hydrogen storage option the lowest LEC is achieved with the pure space system. The reality might lie somewhere in between as pumped hydroelectric storage will be used to the maximal possible amount, the rest done by more expensive, maybe hydrogen storage.

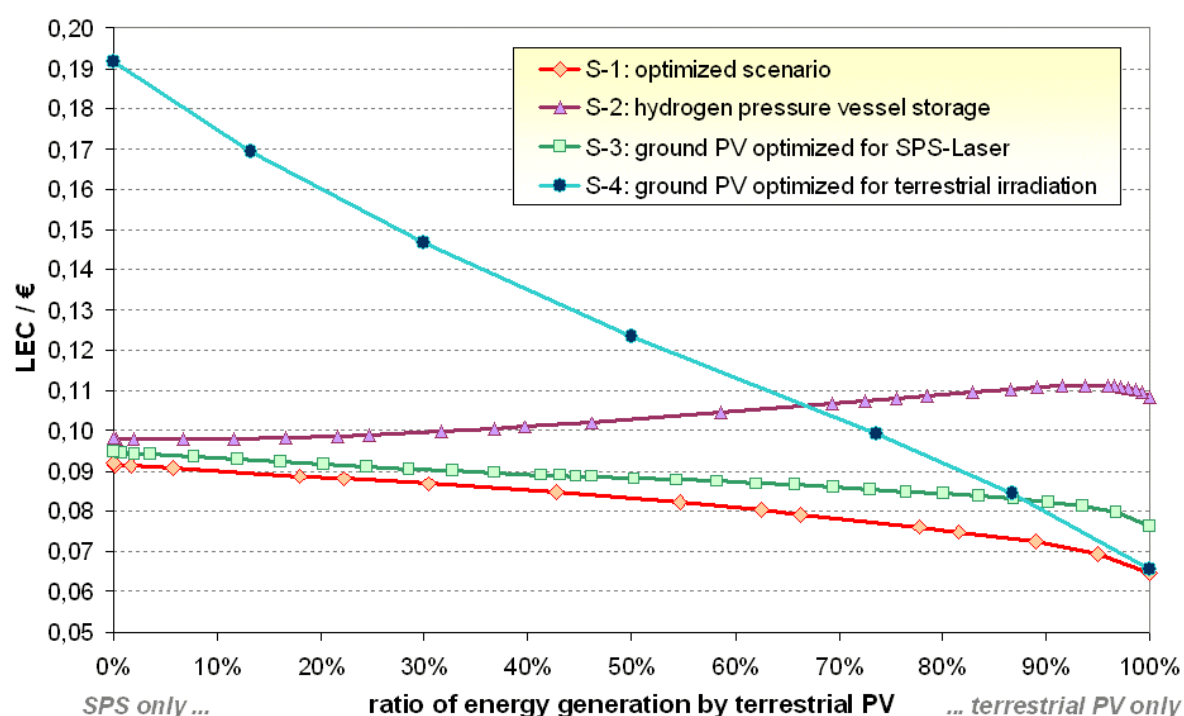


Figure 93. LEC for all scenarios 1-4 for transportation costs of 530 €/kg

## 5.8 Hydrogen Production

Apart from solar generation of electricity for European power supply the option of producing hydrogen using solar energy was investigated. The basic assumptions as well as the results of the calculations are presented here.

### 5.8.1 Assumptions

The assumptions to hydrogen production presented here concern the production technology and the transport of hydrogen via pipeline to Europe. Further assumptions concerning site selection, irradiation, etc. conform to the estimations taken for the scenarios of electricity generation.

#### 5.8.1.1 Production of hydrogen

For hydrogen production the technical definitions of the state-of-the-art and the future technology as well as the economic parameters and cost estimations will be presented.

##### 5.8.1.1.1 Technical definitions H<sub>2</sub> production with today technology

The production of hydrogen as described here is also done by electrolysis with a pressure of 3 MPa and an efficiency of 73% along [Dre00] and [GE03] (see Table 85). The produced hydrogen is stored in underground caverns with 10% losses (compression and heat losses). For a re-electrification of the stored hydrogen a combined cycle power plant with an efficiency of 60% is assumed. Thus, the overall efficiency of the hydrogen chain with about 40% is slightly higher than in paragraph 4.1.3.3.2.1.

Table 85. Technical definition of state-of-the-art hydrogen production [Dre00, GE03]

|                                   |                                                                      |
|-----------------------------------|----------------------------------------------------------------------|
| <b>Electrolysis</b>               | High pressure electrolysis 3 MPa (=30 bars)<br>Efficiency: 73%       |
| <b>Storage</b>                    | Underground storage (caverns)<br>Compression and storage losses: 10% |
| <b>Combined Cycle Power Plant</b> | Efficiency: 60%                                                      |
| <b>Chain</b>                      | Overall efficiency: 40%                                              |

##### 5.8.1.1.2 Technical definitions H<sub>2</sub> production with future technology

With the technology progress until 2020/2030 the efficiency of the electrolysis process is assumed to increase to 77%. The losses in the storage cavern decrease by 2% to 8% whereas for re-electrification then an improved combined cycle power plant or a fuel cell will be used. For them an efficiency of 65% is estimated. Finally, the overall efficiency of the hydrogen chain will increase by 6% to 46% (see Table 86).

Table 86 Technical definition of future hydrogen production (data: [Dre00], own estimations)

|                                    |                                                                     |
|------------------------------------|---------------------------------------------------------------------|
| <b>Electrolysis</b>                | High pressure electrolysis 10 MPa (=100 bar)<br>Efficiency: 77%     |
| <b>Storage</b>                     | Underground storage (caverns)<br>Compression and storage losses: 8% |
| <b>CC Power Plant or Fuel Cell</b> | Efficiency: 65%                                                     |
| <b>Chain</b>                       | Overall efficiency: 46%                                             |

### 5.8.1.1.3 Cost estimations for hydrogen production

The costs for the hydrogen production for a unit of 2 MW are along [Dre00] at 1,750 €/kW (see Table 87). Taking into account a progress ratio of 0.96 this will lead to a price of 900 €/kW for an examined power level of 140 GW. For the storage caverns a price of 1 € per m<sup>3</sup> respectively 0.3 €/kWh of hydrogen is estimated. Costs for the combined cycle power plant are assumed to be 600 €/kW<sub>e</sub> thus leading to overall costs of 2,350 €/kW<sub>e</sub> of power plus 0.3 €/kWh<sub>e</sub> of converted electricity.

Table 87. Costs Assumption for Hydrogen Storage (data: [Dre00], own estimations)

|                       |                                                                             |
|-----------------------|-----------------------------------------------------------------------------|
| <b>Electrolysis</b>   | 1,750 €/kW for 2 MW<br>0.96 progress ratio will lead to 900 €/kW for 140 GW |
| <b>Storage</b>        | 1 €/m <sup>3</sup> or 0.3 €/kWh                                             |
| <b>CC Power Plant</b> | 600 €/kW                                                                    |
| <b>Chain</b>          | 2,350 €/kW + 0.3 €/kWh                                                      |

### 5.8.1.2 Transport of hydrogen

Pipelines were estimated for transportation of hydrogen from the generation site to Europe. Its technological data and the corresponding costs will be presented for state-of-the-art technology as well as for a technology as supposed in 2020/2030.

#### 5.8.1.2.1 Transport of hydrogen at state-of-the-art technology

According to [Dre01] a pipeline for H<sub>2</sub> transport with a transport capacity of 84 billion m<sup>3</sup> GH<sub>2</sub> per year was chosen. For its length of 2500 km twelve compressor stations are necessary to counteract the pressure drop along the line and keep the operation pressure of 7.5 MPa. Along the pipeline length, losses of 18% evolve from the transport. The data is listed in Table 88.

Table 88. Technical Definition for state-of-the-art H<sub>2</sub> Pipeline Transport [Dre01]

|                 |                                                                                                                                                                                 |
|-----------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Pipeline</b> | Length 2500 km<br>Transport losses: 18%<br>Transport capacity: 84 billion m <sup>3</sup> /a GH <sub>2</sub><br>Compressor stations: 12<br>Operation pressure: 7.5 MPa (=75 bar) |
|-----------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

Table 89 shows the assumptions for today investment costs of 2 billion € per length of 1000 km pipeline of the named type. As lifetime of such a pipeline 50 years were estimated. For operation and maintenance 1% of the investment costs are usually needed per year.

Table 89. Cost estimations for state-of-the-art hydrogen pipelines [Dre01]

|                                 |                                                                                                                                         |
|---------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|
| <b>GH<sub>2</sub> Pipelines</b> | Investment costs: 2000 million €/1000 km (84 billion m <sup>3</sup> /a)<br>Lifetime: 50 years<br>O&M costs: 1% p.a. of investment costs |
|---------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|

### 5.8.1.2.2 Transport of hydrogen at future technology in 2020/2030

Until the years 2020/2030 the progress in pipeline technology will lead to higher pressures of 12 MPa in operation. For the same distance of 2500 km then only 10 compressor stations will be required. Whereas the amount of losses can probably be reduced to 8%, its transport capacity will be increased to nearly the double value of 162 billion m<sup>3</sup> GH<sub>2</sub> annually (see Table 90).

Table 90. Technical Definition for H<sub>2</sub> Pipeline Transport [Dre01] in 2020/2030.

|          |                                                                   |
|----------|-------------------------------------------------------------------|
| Pipeline | Length 2500 km                                                    |
|          | Transport losses: 8%                                              |
|          | Transport capacity: 162 billion m <sup>3</sup> /a GH <sub>2</sub> |
|          | Compressor stations: 10                                           |
|          | Operation pressure: 12 MPa                                        |

Coming up with that technological progress a cost reduction of 40% probably will occur (Table 91). Investment costs of 1000 km of the pipeline with this increased capacity of 162 billion m<sup>3</sup> per year will be at 2.3 billion € at a lifetime of still 50 years and again for costs for operation and maintenance 1% of the investment were assumed per year.

Table 91. Cost estimations for hydrogen pipelines in 2020/2030.

|                           |                                                                                     |
|---------------------------|-------------------------------------------------------------------------------------|
| GH <sub>2</sub> Pipelines | Investment costs: 2300 million €/1000 km (162 billion m <sup>3</sup> /a) (40% red.) |
|                           | Lifetime: 50 years                                                                  |
|                           | O&M costs: 1% p.a. of investment costs                                              |

## 5.8.2 Results of solar hydrogen production

The results for solar hydrogen production were calculated for the state-of-the-art technology as well as for technology assumptions for the years 2020/2030 and will be presented in that order.

### 5.8.2.1 Solar hydrogen production today

Hydrogen generation is estimated to take place in generation zone A3 with solar thermal power plants of a net electric capacity of 137 GW<sub>el</sub>. With a conversion efficiency of the electrolysis of 73% and losses of 36% within the transport of hydrogen via pipeline, in average 64 GW of hydrogen arrive in Europe. This corresponds to 560 TWh of hydrogen throughout the year or 152 billion m<sup>3</sup>. Thus levelised costs of 11.4 Cents per kWh hydrogen are achieved at an interest rate of 6%. 35% of the costs derive from hydrogen production, 38% are due to the transport and 26% originate from storage respectively dumping.

Table 92. Calculations of solar hydrogen production for today

|                                 |                        |       |
|---------------------------------|------------------------|-------|
| <b>H<sub>2</sub> Generation</b> |                        |       |
| Average                         | GW                     | 64    |
|                                 | TWh                    | 560   |
| Nominal volume                  | billion m <sup>3</sup> | 152   |
| <b>Assumptions</b>              |                        |       |
| Generation zone                 |                        | A3    |
| Generation type                 | solar thermal          |       |
| ST Capacity                     | GW <sub>el</sub>       | 137   |
| Electrolysis efficiency         |                        | 73%   |
| Transmission losses             |                        | 36%   |
| <b>Resulting LEC</b>            |                        |       |
| Interest rate 6%                | €/kWh <sub>H2</sub>    | 0.114 |
| Interest rate 8%                | €/kWh <sub>H2</sub>    | 0.131 |
| <b>LEC Breakdown for IR=6%</b>  |                        |       |
| Hydrogen generation             |                        | 35.2% |
| Transmission                    |                        | 38.4% |
| Storage and dumping             |                        | 26.4% |

### 5.8.2.2 Solar hydrogen production in 2020/2030

In the future hydrogen production scenario the net power of the solar thermal power plant was estimated to be 130 GW<sub>el</sub>, thus with the increased conversion efficiency of 77% and the decreased losses of only 18%, an average power supply of 84 GW of hydrogen will be delivered to Europe. This accounts to 735 TWh respectively 199 billion m<sup>3</sup>. Also in this case generation zone A3 has been assumed. With the technical and economical improvements levelised costs of 7.4 Cents per kWh hydrogen can be reached at an interest rate of 6%. Then nearly 49% of the costs originate from the production of hydrogen, again 38% belong to transmission and only 13% to dumping and storage.



Table 93. Calculations of solar hydrogen production for 2020/2030

|                                 |                        |               |
|---------------------------------|------------------------|---------------|
| <b>H<sub>2</sub> Generation</b> |                        |               |
| Average                         | GW                     | 84            |
|                                 | TWh                    | 735           |
| Nominal volume                  | billion m <sup>3</sup> | 199           |
| <b>Assumptions</b>              |                        |               |
| Generation zone                 |                        | A3            |
| Generation type                 |                        | solar thermal |
| ST Capacity                     | GW <sub>el</sub>       | 130           |
| Electrolysis efficiency         |                        | 77%           |
| Transmission losses             |                        | 18%           |
| <b>Resulting LEC</b>            |                        |               |
| Interest rate 6%                | €/kWh <sub>H2</sub>    | 0.074         |
| Interest rate 8%                | €/kWh <sub>H2</sub>    | 0.084         |
| <b>LEC Breakdown for IR=6%</b>  |                        |               |
| Hydrogen generation             |                        | 48.9%         |
| Transmission                    |                        | 37.7%         |
| Storage and dumping             |                        | 13.4%         |

It can be possible to generate and transport hydrogen for costs of about 0.05 to 0.06 €/kWh<sub>H2</sub> if cheap wind electricity or solar chemistry is used. However, detailed costs assumptions are difficult for these technologies today.

## 5.9 Conclusions on combined scenarios

For a combination of Space Power Satellites and terrestrial PV systems no advantage could be found within the calculated scenarios. With the taken assumptions, the LEC of a climatic sustainable power supply in 2020/2030 with SPS and/or terrestrial PV systems lies within the same range for both systems. At an optimised scenario the preference due to the lowest levelised electricity costs is depending on detailed values of its parameters which concern e.g. the available future storage system. The capacity of the storage system additionally does not have a high impact on the LEC and can be varied within a big range.

With a cheap storage system like pumped hydroelectric storage the lowest LEC is reached with pure terrestrial PV, with more expensive e.g. hydrogen storage a pure space solution is favourable. However, as Space Power Satellites still are a future option no detailed technological and cost parameters are known. E.g. space transportation costs higher than 530 €/kg shifts the preference clearly to terrestrial systems. Furthermore, Solar Thermal Power Plants were not considered within this comparison and are yet more cost effective than PV power plants. Terrestrial power plants are available and their operability has been proven.

## 5.10 References

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## 6 Viability of the concepts in terms of Energy Payback Times

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### 6.1 General definitions

#### 6.1.1 Definition of Cumulated Energy Demand (CED)

There are several methods to determine the cumulated energy demand (CED) of processes and products (Gürzenich 1997).

- o **Energetical input/output analysis:** Within the energetical input/output analysis the cumulated energy demands of a product are calculated by combining the price of the product with the energy intensities of different productions and service sectors of a national economy. This method does not require details of the considered product, and the CED can be calculated very fast. A disadvantage is that the same CED is assigned to products which belong to the same production sector. Furthermore the CED of the operation and dismantling phases can not be determined.
- o **Method of material balances:** In case of known products and components, the CED can be calculated by combining the mass of the single components with its specific energy demand, obtained from special databases. To get the CED of the whole product, the CED of all components have to be added, completed by the energy needed for manufacturing the product. On the one hand this method is more precisely than the energetical input/output analysis; on the other hand the result depends from the methods used in the different databases for calculating the CED of the components.
- o **Material flow analysis:** The most precise method to determine the CED is to model all material and energy flows in material flow networks (Möller et al. 2001). For every component contained within the product its complete supply chain is analysed („cradle-to-grave“-approach). The operation as well as the dismantling of the product can simply be added. By use of parameters a lot of different scenarios can be calculated with small efforts. The result of the material flow analysis is a life cycle inventory, which can be used to make a complete LCA (life cycle analysis) of the considered product. The energy balance as part of the life cycle inventory balance yields more information on the energy flows than the single value CED. Another advantage of this approach is that in all subnets the same modules can be used, e.g. for steel production, electricity supply, or transportation. This yields much more precise results than by use of „unknown“ components contained in „ready-made“ CEDs from databases.

*Within this project, the method of material flow nets is used to determine the CED. Only in case of lacking subnets for single components the needed energy will be estimated by given CEDs. Chapter 6.1.3 will give some details on material flow nets and the used software.*

#### 6.1.2 Method of Material Flow Networks

In a life cycle assessment (LCA) the *production*, the *operation*, and – if data is available – the *dismantling* of the considered products are modelled. Included are the upstream processes of the most important fuels and materials. In Figure 94 this is clarified by way of a solar thermal power plant's life

cycle. Starting with the production of the solar thermal power plant the upstream processes of both, the used materials and the used electricity, are modelled up to the mining processes of the crude materials. To operate the plant, some more materials are used (for example reimbursement of broken mirrors, lost heat transfer fluid, water for cleaning the mirrors). For the time being the plant's end of life is only considered partly because there do not exist much adequate data and concepts up to now.

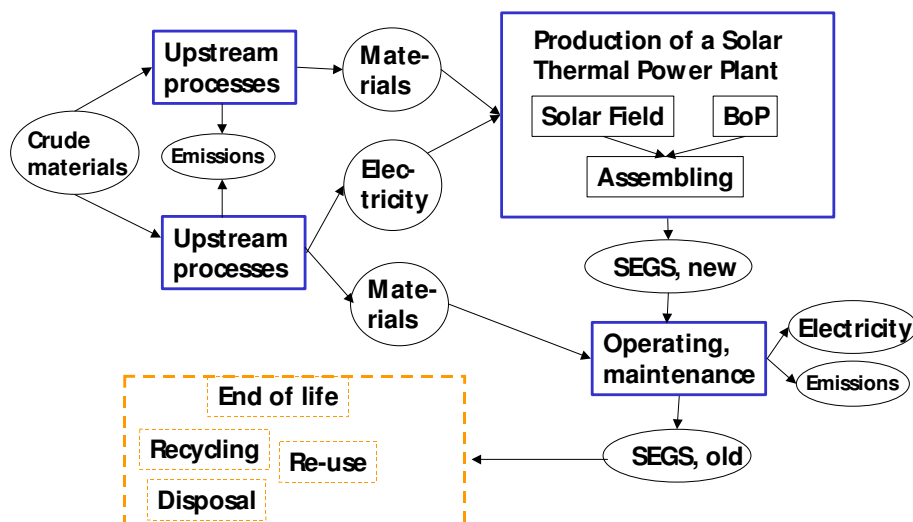


Figure 94. Life cycle of a solar thermal power plant

The LCA of the SEGS plant and the other plants and products used in this study were done using the software Umberto 4.2 (IFEU and IFU 2003). The next figure shows the corresponding top level's notation of the model implemented in Umberto.

## Life Cycle Inventory (Solar Thermal Power Plant)

Modelled with Umberto 4.2®

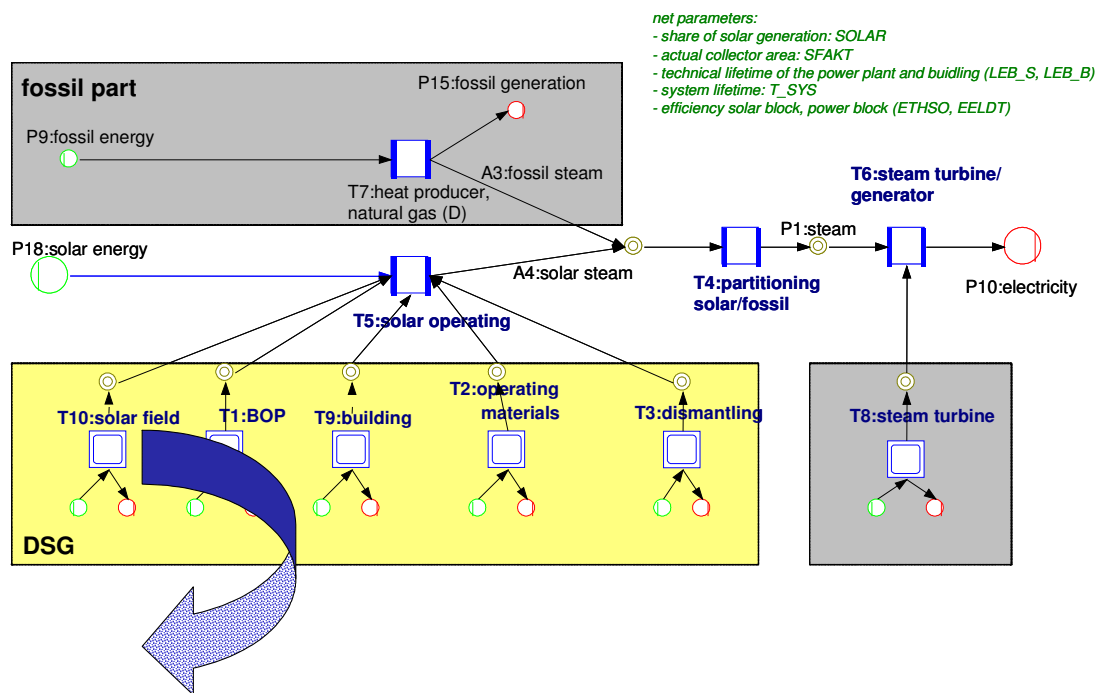


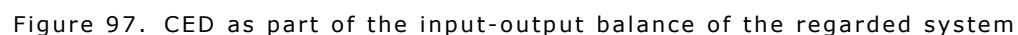
Figure 95. Top level of the model implemented in Umberto

As Figure 95 shows, material flow networks consist of three elements: transitions, places and arrows. *Transitions*, represented by squares, stand for the location of material and energy processes (e.g. *T10:solar\_field* and *T8:steam\_turbine*). Transitions play a vital role in material flow networks because material and energy transformations are the source of material and energy flows. Another defining characteristic of material flow networks is the concept of *places*, represented by circles. Places separate different transitions, which allows a distinct analysis of every transition. *Arrows* show the path of material and energy flows between transitions and places. (Möller et al. 2001)

Every transition can represent another material and energy (sub-)network which results in a hierarchical structure. There exist a lot of sub-networks for the transitions shown above, describing the modelled system in detail. For example, Figure 96 shows the subnet belonging to the transition *T10:solar\_field*, describing the production of the collector field in detail.



After modelling the relevant material and energy flows in a material flow net, the life cycle inventory was created. Finally, the input-output balance of the whole system was calculated. As Figure 97 shows, the CED can be obtained as part of the input “flows” into the system.



### 6.1.3 Definition of Energy Payback Times (EPT)

From the CED, given as one of the results of the LCA, the plant's energy payback time (EPT) can be derived. The EPT is the time in which an energy system produces the same amount of electricity as consumed for its production, operation, and dismantling. For example an EPT of one year means that after one year the consumed energy will be written off. The EPT is defined by the following formula (VDI 2000):

$$EPT = \frac{CED_c}{\left( \frac{E_{net}}{g} - CED_o \right)} \quad (1)$$

where

- $CED_c$  is the cumulative energy demand for the construction [MJ]
- $E_{net}$  is the yearly produced net energy [MJ/y]
- $g$  is the utilisation grade of primary energy source for electricity generation [MJ<sub>el</sub>/MJ]
- $CED_o$  is the annual energy expense for the maintenance [MJ/y].

The result is given in years [y].

Since most products are assumed as to be produced in Germany, an utilisation grade of primary energy source for electricity generation in Germany is used (see the following chapter).

### 6.1.4 LCA Studies, Modules, and Processes Used for this Study

#### General assumptions

Preliminary remark: In the following paragraphs there is differentiated between materials and modules. a “module” means the process of manufacturing this material. For example, the module “steel, high alloyed” means the upstream process of producing steel bars. Output of this module is the material “steel bar, high alloyed”.

The following general assumptions were made:

- o The system lifetime is assumed as 30 years.
- o The technical lifetime of the reference studies were assumed as 20/25 years for photovoltaics, 30 years in case of solar thermal power plants and space systems, 50 years for the HVDC transmission lines and 150 years for the dam/80 years for the rest of the hydro pump storage. To calculate the CED, all systems were scaled to the system lifetime.
- o The time horizon of “state-of-the-art” is defined as 2010, that of the future system as 2030.
- o All equipment is assumed to be produced in Germany, using German or European modules.
- o Therefore for the power plants and for the space systems a ship transport from Hamburg to Casablanca (Morocco) of 2,750 km is assumed. Both, in Germany and in Morocco, a lorry transport of 400 km is assumed. In the following processes the transport is already included: steel, aluminium, chrom, copper.
- o An utilisation grade of primary energy source for electricity generation of 40% in 2010 and of 52.6 % in 2030 is assumed (see description of the electricity mix below).

### LCA studies used for this study

As shown above, the material flow analysis' approach was used to calculate the CED. In general the following types of modules were used in Umberto:

For the “*state-of-the-art*” scenarios the most important modules refer to the situation in the year 2010. Especially, this regards the used electricity mix, the efficiencies, and the recycling rates of the modelled products.

For the “*future*” scenarios only the modifications given in the report of WP 1 and WP 2 were assumed. As Table 94 shows, in most cases this regards only a better efficiency. The space systems were given only for 2030.

In a third scenario named “*2030 dynamic*”, a dynamic CED was considered. This means that in addition to the “technical” changes within the “future” scenarios, the production of the most important modules were adapted to the situation in 2030. Again, this regards changes in the used electricity mix, the efficiencies, and the recycling rates of the modelled products. This approach accounts for the fact, that plants to be built in 2030 will be produced under conditions effective in the year 2030.

Figure 98 shows this procedure at a glance:

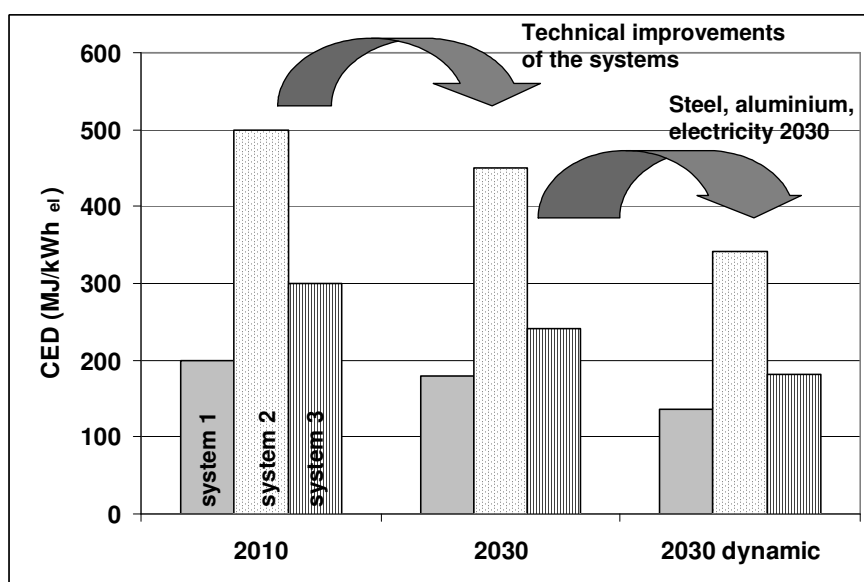


Figure 98. Dynamic calculations of the CED

Besides the changes assumed for the “future” scenarios, Table 94 gives an overview on the products and the data sources that had to be considered within the scenarios of WP 1, WP 2, and WP 3.



Table 94. Sources of the LCA studies used to calculate the CED

| Product               | Type of LCA     | Reference case |             |          | Source                     | „2020/2030“ vs. „state-of-the-art“                                                 |
|-----------------------|-----------------|----------------|-------------|----------|----------------------------|------------------------------------------------------------------------------------|
|                       |                 | Load           | Funct. Unit | Lifetime |                            |                                                                                    |
| SEGS parabolic trough | Complete LCA    | 80 MW          | 1 kWh       | 30 y     | Böhnke 1997, Reinhold 1997 | better efficiency, less thermal storage                                            |
| Photovoltaics         | Complete LCA    | 1 kW           | 1 kW        | 25/20 y  | ECLIPSE 2004               | better efficiency, other technology (multi-junction instead of single-crystalline) |
| Hydro pump storage    | Complete LCA    | average        | 1 kWh       | 150/80 y | ecoinvent 2003             | better efficiency                                                                  |
| HVDC lines            | Complete LCA    | 1.6 GW         | 1 km        | 50 y     | Pehnt 2002                 | ---                                                                                |
| HVAC lines            | Complete LCA    | average        | 1 km        | ?        | ecoinvent 2003             | ---                                                                                |
| Orbital system        | LCA, partly CED | 10 GW          | 1 kW        | 30 y     | EADS 2004c                 | only “2020/2030”                                                                   |
| Launch vehicles       | LCA, partly CED | 10 GW          | 1 kW        | 30 y     | EADS 2004c                 | only “2020/2030”                                                                   |

### Most important modules used for the study

In the following the most important modules used in this study and their main assumptions are described. It was assumed that most components will be produced in Germany. If available, modules describing the situation in Germany are used.

- o Electricity mix:
  - o *2010\_Electricity\_Mix\_D*: This mix describes the situation in the year 2010 under the assumption of a reference development regarding the electricity production in Germany. The overall efficiency accounts for 40%, the share of renewables in the primary energy resources is 6%.
  - o *2030\_Electricity\_Mix\_D*: This mix describes a possible situation in the year 2030 under the conditions of a sustainable production of electricity in Germany. This mix results from a study for the German Federal Agency in which several scenarios of a future electricity supply in Germany were investigated (Fischedick and Nitsch 2002). Modifications compared with the situation in 2010 are adapted shares of the energy resources, better efficiencies of the power plants, and a reduction of the direct emissions of the fossil power plants. The overall efficiency accounts for 52.6%, the share of renewables in the primary energy resources is 26%.

These electricity mixes are included in the most important processes like production of steel, aluminium, or flat glass.

- o Steel:
  - o *2010\_Steel\_bar*: The process of steel production refers to the situation in Germany in the nineties. The actual recycling quota of steel in Germany and worldwide are 43% and 46%, respectively (BDSV 2002). Steel from automobiles has a recycling quota of 75%. In the module “2010\_Steel\_bar” a recycling quota of 46% is assumed for all types of steel. The “2010\_Electricity\_Mix\_D” is used.

- o *2030\_Steel\_bar*: The recycling quota is increased to 75% and the “2030\_Electricity\_Mix\_D” is used for all types of steel.
- o Aluminium:
  - o *2010\_Aluminium\_component*: The process of aluminium production refers to the situation in Europe in the nineties, described by the European Aluminium Association (Boustead 2000), who declared an electricity consumption of 15,590 kWh/t for primary aluminium, 354 kWh/t for secondary aluminium, and a share of hydro electricity of 53%. The recycling quota depends on the type and configuration of the products. In Germany 72% of aluminium package, 85% of the aluminium used in the building industry, and 87% of the aluminium used in the electrical engineering are recycled (GDA and Aluminiumindustrie 2002). Therefore a recycling quota of 85% is assumed for 2010. For the recycling of the aluminium scrap and the production of the components the “2010\_Electricity\_Mix\_D” is used.
  - o *2030\_Aluminium\_component*: The recycling quota is increased to 90%; for the production of the components the “2030\_Electricity\_Mix\_D” is used. Since the electricity mix used for the production of the aluminium has already a very high share of renewables (hydro electricity), this mix is not modified. In contrast the electricity consumption of the electrolysis is decreased by 7% to 14,500 kWh/t primary aluminium, according to Rombach et al. 2001.
- o Liquid Hydrogen (LH<sub>2</sub>):
  - o *2010\_LH<sub>2</sub>*: The chain for LH<sub>2</sub> was taken from the very new study concawe et al. 2003. It contains the steps “central electrolyser” with “Electricity (EU-mix, LV)”, “liquefaction”, “liquid hydrogen long-distance-transport”, and “liquid hydrogen distribution and dispensing” (named as “EMEL1/LH1”). The CED calculated in the study as 3.97 MJ/MJ does neither consider the energy involved in building the facilities and the vehicles, nor the end of life aspects. Therefore an addition of 10% was assumed to consider these aspects.
  - o *2030\_LH<sub>2</sub>*: Instead of the EU-electricity mix used in concawe et al. 2003 (efficiency 35%), the “2030\_Electricity\_Mix\_D” with an efficiency of 52.6% was used.
- o Liquid Oxygen (LO<sub>2</sub>):
  - o *2010\_LO<sub>2</sub>*: To calculate the CED, the electricity demand required to produce one kg of LO<sub>2</sub> given by EADS was multiplied with the efficiency of the “2010\_Electricity\_Mix\_D”.
  - o *2030\_LO<sub>2</sub>*: Instead of the “2010\_Electricity\_Mix\_D” the “2030\_Electricity\_Mix\_D” was used.
- o CFRP (carbon fiber reinforced plastics):
  - o *2010\_CFRP*: The CED for CFRP refers to a Achternbosch et al. 2003. In this very actual study the mass and energy consumption related to the production, use, and recycling of a CFRP fuselage was analysed and modelled for the first time. The main process steps from the mining of the raw materials to the final product were identified. For this project only the production of the carbon fibres and the ensuing production of CFRP via single-line-injection, a process developed by DLR, were taken into account. The process refers to the actual German electricity mix.
  - o *2030\_CFRP*: The CED was reduced by 24% all-inclusive, an average parameter for the transition from “state-of-the-art”-modules to “2030 dynamic” modules.
- o Copper:
  - Copper, primary*: For primary copper a module from the database GaBI (PE and IKP 1998)

was used.

*Copper, secondary*: For secondary copper a module from Umberto was used. In Germany 40% of the consumed copper is secondary copper. Referring to components there is a much higher recycling rate (DKI 1997). Since the detailed rate is unknown, a rate of 80% is chosen according to the situation in Japan (Ayres et al. 2000).

- o Recycling processes: *Recycling processes* are modelled as a closed loop accordingly to ISO 14,041. This means the replacement of a part of the primary material through secondary material.

### **Overview on the used CED**

Table 95 gives an overview on the cumulated energy demands for the most important materials used in this study.

Table 95. Overview on the used materials and their CED

| Energy                       | CED<br>MJ/kWh | Source           | Remarks                                                                                               |
|------------------------------|---------------|------------------|-------------------------------------------------------------------------------------------------------|
| <b>Electricity</b>           |               |                  |                                                                                                       |
| 2010_Electricity_Mix_HV_D    | 8.96          | IFEU             | Reference scenario Germany, g = 40%                                                                   |
| 2010_Electricity_Mix_MV_D    | 9.11          | IFEU             | Reference scenario Germany, g = 40%                                                                   |
| 2010_Electricity_Mix_LV_D    | 9.37          | IFEU             | Reference scenario Germany, g = 40%                                                                   |
| 2030_Electricity_Mix_HV_D    | 7.04          | IFEU             | Sustainable scenario Germany, g = 52.6%                                                               |
| 2030_Electricity_Mix_MV_D    | 7.16          | IFEU             | Sustainable scenario Germany, g = 52.6%                                                               |
| 2030_Electricity_Mix_LV_D    | 7.37          | IFEU             | Sustainable scenario Germany, g = 52.6%                                                               |
| Material                     | CED<br>MJ/kg  | Source           | Remarks                                                                                               |
| <b>Steel</b>                 |               |                  |                                                                                                       |
| 2010_Steel_bar, high alloyed | 58.91         | IFEU             | Recycling quota of 43%, 2010_Electricity_Mix                                                          |
| 2010_Steel_bar, low alloyed  | 28.37         | IFEU             | Recycling quota of 43%, 2010_Electricity_Mix                                                          |
| 2010_Steel_bar, not alloyed  | 22.27         | IFEU             | Recycling quota of 43%, 2010_Electricity_Mix                                                          |
| 2030_Steel_bar, high alloyed | 51.16         | IFEU             | Recycling quota of 75%, 2030_Electricity_Mix                                                          |
| 2030_Steel_bar, low alloyed  | 19.47         | IFEU             | Recycling quota of 75%, 2030_Electricity_Mix                                                          |
| 2030_Steel_bar, not alloyed  | 13.79         | IFEU             | Recycling quota of 75%, 2030_Electricity_Mix                                                          |
| <b>Space systems</b>         |               |                  |                                                                                                       |
| Electronics                  | 144           | EADS             |                                                                                                       |
| GaAs Diode laser arrays      | 360 / 54      | EADS             |                                                                                                       |
| 2010_LH <sub>2</sub>         | 523           | concawe          | Central Electrolysis + liquefaction + road + EU-Mix 2010                                              |
| 2030_LH <sub>2</sub>         | 348           | concawe          | Central Electrolysis + liquefaction + road + 2030_Electricity_Mix                                     |
| 2010_LO <sub>2</sub>         | 8.91          | EADS/<br>Umberto | Electrolysis + air rectify. + liquefaction + 2010_Electricity_Mix                                     |
| 2030_LO <sub>2</sub>         | 6.77          | EADS/<br>Umberto | Electrolysis + air rectify. + liquefaction + 2030_Electricity_Mix                                     |
| 2010_CFRP                    | 551           | FZK              | carbon fibres and production of CFRP via single-line-injection                                        |
| 2030_CFRP                    | 420           | FZK              | 2030_Electricity_Mix                                                                                  |
| Solar Cells (GaAs)           | 360           | EADS             | Thin cells for orbital segment                                                                        |
| <b>Other materials</b>       |               |                  |                                                                                                       |
| 2010_Aluminium_component     | 54.46         | IFEU             | Recycling quota of 85%, 2010_Electricity_Mix                                                          |
| 2030_Aluminium_component     | 38.22         | IFEU             | Recycling quota of 90%, 2030_Electricity_Mix<br>reduction of electricity consumption for electrolysis |

|                                                                                                                  |        |           |                      |
|------------------------------------------------------------------------------------------------------------------|--------|-----------|----------------------|
| 2010_Ceramics                                                                                                    | 6.94   | ecoinvent | 2010_Electricity_Mix |
| 2030_Ceramics                                                                                                    | 6.72   | ecoinvent | 2030_Electricity_Mix |
| Concrete                                                                                                         | 0.79   | IFEU      |                      |
| Copper wire (as primary copper)                                                                                  | 37.47  | IFEU      |                      |
| Copper, secondary                                                                                                | 20.55  | Umberto   |                      |
| 2010 Fibreglass                                                                                                  | 25.06  | ecoinvent | 2010_Electricity_Mix |
| 2010_Flat glass                                                                                                  | 10.28  | ecoinvent | 2010_Electricity_Mix |
| 2030_Flat glass                                                                                                  | 9.95   | ecoinvent | 2030_Electricity_Mix |
| Phenol                                                                                                           | 104.41 | Umberto   |                      |
| Portland cement                                                                                                  | 3.96   | Umberto   |                      |
| PU foam, rigid                                                                                                   | 63.21  | Umberto   |                      |
| 2010 Rock wool                                                                                                   | 20.42  | ecoinvent | 2010_Electricity_Mix |
| 2030 Rock wool                                                                                                   | 18.63  | ecoinvent | 2030_Electricity_Mix |
| Vulcanised rubber                                                                                                | 66.61  | Umberto   |                      |
|                                                                                                                  |        |           |                      |
| Sources                                                                                                          |        |           |                      |
| Umberto = ifu and ifeu 2003 / EADS = EADS 2004c / concawe = concawe et al. 2003 / FZK = Achternbusch et al. 2002 |        |           |                      |

## 6.2 Energy Balance Analyses of Space Systems

### 6.2.1 Data Sources

Taking the results from WP 1, WP 2, and WP 3 (EADS 2004b), the general energy gain for space systems to be modelled looks as shown in Figure 99.

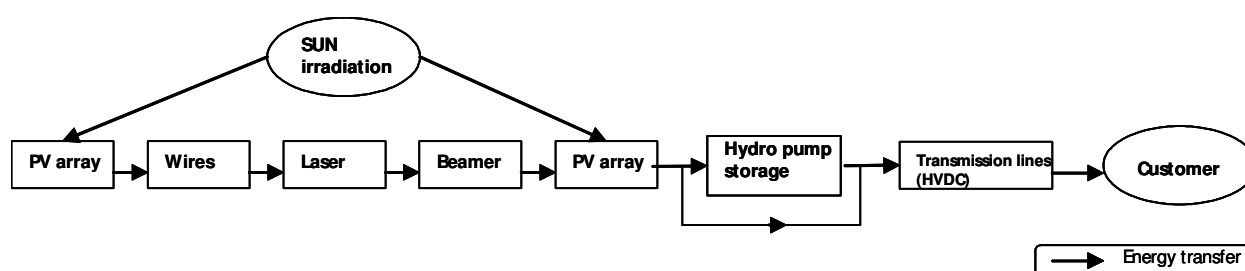


Figure 99. Energy gain for space-terrestrial systems

The following general assumptions were made:

- o Only future systems (2030) were considered.
- o No distinction between base load and remaining load was made.
- o Since the chosen space-based solar power system uses a laser to transfer the energy from space to the earth, no space-only system is possible. In every case a terrestrial system is necessary to receive the laser irradiance, dimensioned for the space-based system.

The input data required to calculate the LCA and the CED was taken from the “technical report”, delivered by EADS 2004b (chapter 4.3, table 1 and several pictures), actualised by EADS 2004c. The

data was composed in such a way that it could serve as the input data to the software Umberto. Addendum 8.3.2 shows both, the data used for the calculation of the space systems and the results of CED and EPT calculation. As mentioned above, the CED of the single products were calculated by using LCA models, if possible. In cases no LCA were available, given CED of single products were used. In the following the data sources of these models are described.

### **6.2.1.1 Orbital System**

Table 96 shows the data used to model the orbital system. Basis of the calculations are the materials and mass data given by EADS, shown in columns 1 to 3 and 5. The following assumptions were made:

- o To model the inventory in Umberto, the mass data given by t/(10 GW SPS) was converted to kg/(kW SPS).
- o The CED given by EADS (column 5) were used only in case no data was available in the Umberto database because the sources of the given values are not known and therefore not reviewable. All cases in which these values are used are marked in column 9.
- o In case modules were available referring to the situation in 2030, these CED were used for “2030 dynamic”.
- o The resupply over 30 years was taken into account by adding 18% on all items (0.6% per year), as given by EADS.
- o Additionally, for all components a supplement of 10 percent of the required energy was added to model the process energy used for the assembly of the components.

Table 96. Inventory of the space system

| 1                           | 2                                             | 3                               | 4           | 5                       | 6       | 7             | 8                                          | 9      | 10                  | 11                          | 12      |
|-----------------------------|-----------------------------------------------|---------------------------------|-------------|-------------------------|---------|---------------|--------------------------------------------|--------|---------------------|-----------------------------|---------|
| Segment                     | Material                                      | Mass<br>(EADS)<br>t/(10GW SPS)) | kg/(kW SPS) | CED<br>(EADS)<br>kWh/kg | MJ/kg   | 2030<br>MJ/kg | CED used in model<br>2030 dynamic<br>MJ/kg | Remark | 2030<br>MJ/(kW SPS) | 2030 dynamic<br>MJ/(kW SPS) | Remarks |
| <b>Orbital system, PV</b>   |                                               |                                 |             |                         |         |               |                                            |        |                     |                             |         |
| Module Cover Glass          | 20 µm float glass foil                        | 5,756                           | 0.576       | 7.50                    | 27.00   | 27.00         | 27.00                                      |        | 15.54               | 15.54                       |         |
| Solar Cells (GaAs)          | 5 µm GaAs                                     | 2,491                           | 0.249       | 100.00                  | 360.00  | 360.00        | 360.00                                     |        | 89.68               | 89.68                       |         |
| Collection Grids            | 1 µm Copper                                   | 79                              | 0.008       | 15.60                   | 56.16   | 56.16         | 56.16                                      |        | 0.44                | 0.44                        |         |
| Insulation Foils            | 6 µm Kapton foil                              | 731                             | 0.073       | 12.60                   | 45.36   | 45.36         | 45.36                                      |        | 3.31                | 3.31                        |         |
| Substrate Foils             | 8 µm low alloyed steel                        | 7,085                           | 0.709       | 15.65                   | 56.34   | 56.34         | 56.34                                      |        | 39.92               | 39.92                       |         |
| Reflector Foils             | 6 µm Kapton foil                              | 1,461                           | 0.146       | 12.60                   | 45.36   | 45.36         | 45.36                                      |        | 6.63                | 6.63                        |         |
| Reflection layer            | 1µm aluminium                                 | 598                             | 0.060       | 24.50                   | 88.20   | 88.20         | 88.20                                      |        | 5.27                | 5.27                        |         |
| Total                       |                                               |                                 |             |                         |         |               |                                            |        | 160.79              | 160.79                      |         |
| 10% process energy          | electricity                                   |                                 |             |                         |         |               |                                            |        | 16.079              | 16.079                      |         |
| <b>Orbital System, rest</b> |                                               |                                 |             |                         |         |               |                                            |        |                     |                             |         |
| Suspension                  | CFRP tension cables                           | 216                             | 0.022       | 7.80                    | 28.08   | 551.00        | 420.00                                     | F      | 11.90               | 9.07                        |         |
|                             | Springs: low alloyed steel                    | 22                              | 0.002       | 15.60                   | 56.16   | 28.40         | 19.47                                      | U      | 0.06                | 0.04                        |         |
|                             | Spring casings: CFRP                          | 13                              | 0.001       | 15.60                   | 56.16   | 551.00        | 420.00                                     | F      | 0.72                | 0.55                        |         |
| Secondary Bus Bars          | Bare Aluminium Al 99.5 cables                 | 4,390                           | 0.439       | 24.50                   | 88.20   | 54.50         | 38.22                                      | U      | 23.93               | 16.78                       |         |
| Laser System                | GaAs Diode stacks&connections                 | 1,830                           | 0.183       | 100.00                  | 360.00  | 360.00        | 360.00                                     |        | 65.88               | 65.88                       |         |
|                             | Laser optics and fibre optics                 | 20,670                          | 2.067       | 15.00                   | 54.00   | 54.00         | 54.00                                      |        | 111.62              | 111.62                      |         |
| Thermal Control Radiators   | 44% Al 99.5 + 56% Lithium                     | 29,960                          | 2.996       | 24.50                   | 88.20   | 88.20         | 88.20                                      |        | 264.25              | 264.25                      |         |
| Electronics                 |                                               | 1,128                           | 0.113       | 40.00                   | 144.00  | 144.00        | 144.00                                     |        | 16.24               | 16.24                       |         |
| Attitude & Position Control | Low alloyed stainless steel                   | 3,490                           | 0.349       | 15.60                   | 56.16   | 28.40         | 19.47                                      | U      | 9.91                | 6.80                        |         |
| Total                       |                                               |                                 |             |                         |         |               |                                            |        | 504.51              | 491.22                      |         |
| 10% process energy          | electricity                                   |                                 |             |                         |         |               |                                            |        | 50.451              | 49.122                      |         |
| <b>Launch Vehicles</b>      |                                               |                                 |             |                         |         |               |                                            |        |                     |                             |         |
| Tank shells                 | CFRP (5.4mØ tubes with end domes)             | 22,023                          | 2.202       | 7.80                    | 28.08   | 551.00        | 420.00                                     | F      | 1213.47             | 924.97                      |         |
| Payload shrouds             | CFRP (5.4mØ tubes with end domes)             | 11,574                          | 1.157       | 7.80                    | 28.08   | 551.00        | 420.00                                     | F      | 637.73              | 486.11                      |         |
| Cryo-Insulation             | PU-foam                                       | 2,880                           | 0.288       | 9.50                    | 34.20   | 63.21         | 63.21                                      | U      | 18.20               | 18.20                       |         |
| Fuel: Liquid Hydrogen       | LH2: electrolysis + liquefaction              | 167,180                         | 16.718      | 54.5 *                  | 196.2 * | 523.00        | 348.00                                     | C      | 8743.51             | 5817.86                     |         |
| Oxidiser: Liquid Oxygen     | LO2: electr. + air rectify. & liquef.         | 1,072,520                       | 107.252     | 0.9 *                   | 3.24 *  | 8.91          | 6.77                                       | (U)    | 955.62              | 726.20                      |         |
| Total                       |                                               |                                 |             |                         |         |               |                                            |        | 11568.53            | 7973.35                     |         |
| 10% process energy          | electricity (without LH2+LO2)                 |                                 |             |                         |         |               |                                            |        | 186.940             | 142.928                     |         |
| <b>RAAM (14 modules)</b>    |                                               |                                 |             |                         |         |               |                                            |        |                     |                             |         |
|                             | Aluminium, Copper,CFRP                        | 508.5                           | 0.051       | 24.50                   | 88.20   |               |                                            |        |                     |                             |         |
|                             | therein:                                      |                                 |             |                         |         |               |                                            |        |                     |                             |         |
|                             | 45% high alloyed steel                        |                                 | 0.023       |                         |         | 58.91         | 51.16                                      | U      | 1.35                | 1.17                        |         |
|                             | 5% Copper                                     |                                 | 0.003       |                         |         | 23.93         | 23.93                                      | U      | 0.06                | 0.06                        |         |
|                             | 22% Aluminium                                 |                                 | 0.011       |                         |         | 54.46         | 38.22                                      | U      | 0.61                | 0.43                        |         |
|                             | 22% CFRP                                      |                                 | 0.011       |                         |         | 551.00        | 420.00                                     | F      | 6.16                | 4.70                        |         |
|                             | 6% Cesium                                     |                                 | 0.003       |                         |         | 113.37        | 113.37                                     | U,**   | 0.35                | 0.35                        |         |
| Total                       |                                               |                                 |             |                         |         |               |                                            |        | 8.53                | 6.70                        |         |
| 10% process energy          | electricity                                   |                                 |             |                         |         |               |                                            |        | 0.853               | 0.670                       |         |
| <b>Resupply</b>             | 0.6% on all items per year = 18% per 30 years |                                 |             |                         |         |               |                                            |        |                     |                             |         |

Values originally given by EADS are printed in italics  
 \*: only electricity consumption  
 \*\*: instead of Cesium the material SiC was used  
 C: actual CED taken from Concawe et al. 2003  
 F: actual CED taken from FZK study (Achterbosch et al. 2003)  
 U: actual CED taken from software Umberto

### 6.2.1.2 Ground System

For the ground part of the space system the same components as used for the terrestrial systems were considered. These are

#### Photovoltaics

To model the ground PV an amorphous silicon thin film cell with module triple junction, a module efficiency of 9%, a CED of 9,940 MJ/kW<sub>p</sub>, and a life time of 20 years was chosen from ECLIPSE 2004. The efficiency was scaled up to 15% as required for the future systems. The lifetime was scaled up to the system lifetime of 30 years. Only one PV system used for both the daylight and the laser beam was modelled.<sup>1</sup>

#### Hydro pump storage

The hydro pump storage was modelled by using data from the Swiss ecoinvent database (ecoinvent 2003). From the available datasets the “reservoir hydropower plant for non alpine regions” was chosen. In this study the data from Swiss dams have been directly applied to preliminary describe dam-mixes in non-alpine regions, increasing the uncertainty factors somewhat. Non alpine regions are all European countries except of Switzerland, Austria, Italy, and France. It is justifiable to adopt this module to the terrestrial systems because the assumed solar power plants will be located in the highlands in eastern Egypt at an amount between some 100 metres and 1,500 m.

Considering the difficulty to clearly separate within the Swiss dams system for some of the dams function for normal electricity generation from pumping storage, the same basic information has been used for the modules describing the two functions. The data refers to plant construction of a mix of types of dams built between 1945 and 1970, therefore they might not be representative for more modern construction, nor for an individual type.

Since there was only data for a hydro pump storage at an average size, the model was calculated for an storage output of one kWh and linearly applied to the results from WP 1 and WP 2. Storage efficiency was not given.

#### Transmission line HVDC

The transmission line HVDC was modelled by using data from (Pehnt 2002). Pehnt refers to the inventory data for a transmission line (500 kV, 1.6 GW<sub>el</sub>) built from Borneo to Malaysia, based on data from Siemens and Fichtner (Germany). For this study these data were adopted to the required conditions by scaling the load to 5 GW<sub>el</sub> and by scaling to the lifetime of 30 years. Since Pehnt did not break up the inventory data into lines and periphery, it was assumed that the given data for “steel, high alloyed” and for “aluminium” referred to the lines only, the other data referred to the periphery. Consequently, “steel, high alloyed” and “aluminium” were scaled linearly up whereas the other data was not modified. The model was calculated for a length of one km and and linearly applied to the required data. Data on the assumed losses was not given.

## 6.2.2 Results

The energy payback times were calculated for the space systems with 10, 25, 50, 75, and 100 GW load. Table 97 shows the combination of SPS and ground parts. The numbers of SPS and ground PV

<sup>1</sup> Description of the used future PV system: “The other developments consider a triple structure composed of 3 p-i-n layers. This configuration leads to improve the cells efficiency (7-9%). In the database a 9% cell efficiency has been considered as future case. Thanks to technological improvement in deposition processes the active layers’ thickness seems to remain the same of the single structure one, so no higher amount of materials is required; it has been assumed that energy consumption remain unchanged too (no detailed data). Since we assumed no higher input data, no specific unit processes have been made for this case.” (ECLIPSE 2004)



were given by EADS 2004b. Storage output and number of HVAC transmission lines were given only for 10 GW and 25 GW and had to be scaled up to the other system loads.

Table 97. Combination of orbital and terrestrial systems

| System load<br>[GW] | # SPS | # Ground PV | Storage output<br>[GWh] | # HVAC<br>5 GW 5,000 km |
|---------------------|-------|-------------|-------------------------|-------------------------|
| 10                  | 1     | 1           | 200                     | 2                       |
| 25                  | 3     | 1           | 500                     | 5                       |
| 50                  | 6     | 2           | 1,000                   | 10                      |
| 75                  | 9     | 3           | 1,500                   | 15                      |
| 100                 | 12    | 4           | 2,000                   | 20                      |

Table 98 shows the energy payback times. They were calculated by adding the CED for the single components and applying formula 1. Intermediate results are shown in addendum 8.3.2.

Table 98: Energy payback times of the space scenarios

| Scenario period | GW     | 10  | 25  | 50  | 75  | 100 |
|-----------------|--------|-----|-----|-----|-----|-----|
| 2010            | months | --- | --- | --- | --- | --- |
| 2030            | months | 4.4 | 3.9 | 3.9 | 3.9 | 3.9 |
| 2030 dynamic    | months | 4.2 | 3.7 | 3.7 | 3.7 | 3.7 |

The following results can be drawn:

- o The calculations of the systems > 10 GW yields all the same EPT of 3.9 months for “2030” and 3.7 months for “2030 dynamic”, respectively. They decrease by 12%, compared with the EPT for the 10 GW scenario. The reason is the delay in the scaling of the numbers of ground PV as shown in Table 97 (for 25 GW the same size of ground PV is used as for 10 GW).
- o The EPT of the “2030 dynamic” scenarios decrease by 15% compared with the scenario “2030”.

Table 99 gives an overview on the component’s share in the EPT. Whereas the SPS dominates the EPT within the 10 GW scenario with 44%, this share increases within the following scenarios to 61%. Again, this results from the delay in the scaling of the numbers of ground PV. Accordingly, the share of the transmission lines increases to 22%.

Table 99. Shares of CED in the space systems’ components (“2030 dynamic”)

| Space systems (2030 dynamic) | GW | 10    | 25    | 50    | 75    | 100   |
|------------------------------|----|-------|-------|-------|-------|-------|
| SPS                          | %  | 44.0  | 61.0  | 61.0  | 61.0  | 61.0  |
| Ground PV                    | %  | 36.9  | 17.1  | 17.1  | 17.1  | 17.1  |
| Lines to storage (HVAC)      | %  | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Storage                      | %  | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 |
| Transmission lines (HVDC)    | %  | 19.0  | 22.0  | 22.0  | 22.0  | 22.0  |

Figure 100 shows the allocation of the EPT within the orbital part of the space system. It is clearly visible that the launch vehicles dominate the EPT with 90% (therein 80% caused by the production of

the liquid hydrogen). The laser system and the orbital PV each accounts for 2%, the orbital rest for 6%, and the RAAM for 0.08%.

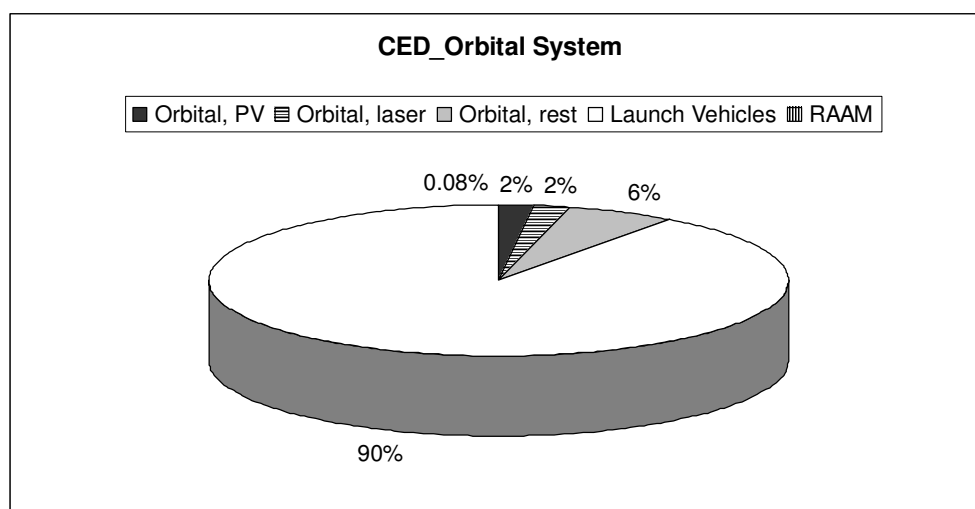


Figure 100. Shares of CED in the orbital components ("2030 dynamic")

## 6.3 Energy Balance Analyses of Terrestrial Systems

### 6.3.1 Data Sources

Taking the results from WP 1.1 (base-load, terrestrial state-of-the-art concepts), WP 1.2 (base-load, terrestrial power concepts for 2020/2030), WP 2.1 (peak-load, terrestrial state-of-the-art concepts), and WP 2.2 (peak-load, terrestrial power concepts for 2020/2030), the general energy gain for terrestrial systems to be modelled looks as shown in Figure 101.

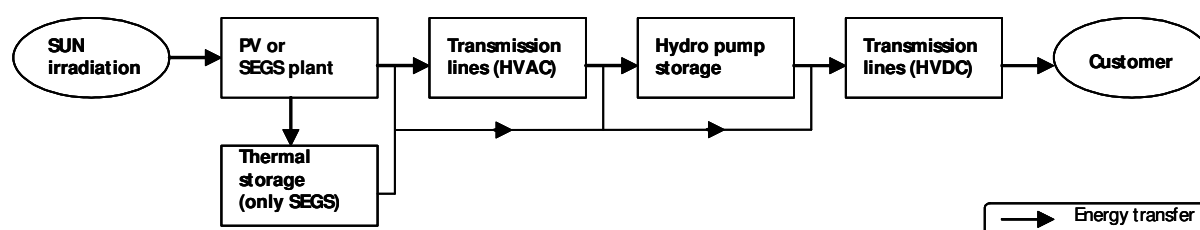


Figure 101. Energy gain for terrestrial systems

The input data required to calculate the LCA and the CED was taken from the "detailed calculation results" delivered by DLR 2004 (WP 1.1, WP 1.2, WP 2.1, and WP 2.2). The data given in the tables 51 to 150 of the report was composed in such a way that it could serve as input data to the software Umberto. Addendum 8.3.1 shows both, the data used for the calculation of the terrestrial systems and the results of CED and EPT calculation. As mentioned above, the CED of the single products were calculated by using LCA models. In the following the data sources of these models are described. All components were scaled to the same lifetime of 30 years.

### **Solar thermal power plant**

As a solar thermal system a SEGS plant (80 MW<sub>el</sub>) was modelled. Most data was taken from Böhnke 1997 and Reinhold 1997 who worked with original data from the producer. These data were supplemented by own inquiries e.g. on new methods for cleaning the mirrors (Cohen et al. 1999). The plant contains a dry cooling tower and a thermal concrete slab storage. The original data refers to a location in the south-east of Morocco with a global irradiation of 2,654 kWh/(m<sup>2</sup>,a) and a solar field of 694,118 m<sup>2</sup>.

For this study these data were adopted to the conditions given by the results of WP 1 and WP 2 by scaling the whole plant to 100 MW<sub>el</sub> and increasing the solar field to the required size. The required load was modelled by combining of several 100 MW blocks. Different combinations of solar field size, efficiencies, and thermal storage capacity were calculated and applied to the results from WP 1 and WP 2.

### **Photovoltaics**

To model the photovoltaics scenarios, two types of photovoltaics were taken from the recent constructed ECLIPSE database (ECLIPSE 2004):

- A monocrystalline silicon cell (PL800 from Eurosolare with a Solcon 3400 HE Inverter) with a module efficiency of 13%, a CED of 28,200 MJ/kW<sub>p</sub>, and a life time of 25 years was chosen to model the situation defined for “2010”. The efficiency was scaled up to 14% as required. The lifetime was scaled up to the system lifetime of 30 years.
- As a future system, an amorphous silicon thin film cell with module triple junction, a module efficiency of 9%, a CED of 9,940 MJ/kW<sub>p</sub>, and a life time of 20 years was chosen. The efficiency was scaled up to 15% as required for the future systems. The lifetime was scaled up to the system lifetime of 30 years.

Both systems include the modules, the balance of system, and the end-of-life. The modules are provided to retrofit a tilted roof. Therefore an additional elevation has to be taken into consideration to build them into the desert.

Since the data given by ECLIPSE is referring to one kW<sub>el</sub>, the required load was modelled by linear scaling.

### **Hydro pump storage**

The hydro pump storage was modelled by using data from the Swiss ecoinvent database (ecoinvent 2003). From the available datasets the “reservoir hydropower plant for non alpine regions” was chosen. In this study the data from Swiss dams have been directly applied to preliminarily describe dam-mixes in non alpine regions, increasing the uncertainty factors somewhat. Non-alpine regions are all European countries except of Switzerland, Austria, Italy, and France. It is justifiable to adopt this module to the terrestrial systems because the assumed solar power plants will be located in the highlands in the eastern Egypt at an amount between some 100 metres and 1,500 m.

Considering the difficulty to clearly separate within the Swiss dams system for some of the dams function for normal electricity generation from pumping storage, the same basic information has been used for the modules describing the two functions. The data refers to plant construction of a mix of types of dams built between 1945 and 1970, therefore they might not be representative for more modern construction, nor for an individual type.

Since there was only data for a hydro pump storage at an average size, the model was calculated for an storage output of one kWh and linearly applied to the results from WP 1 and WP 2. Storage efficiency was not given.

### Transmission line HVAC

The transmission line HVAC was modelled by using data from the Swiss ecoinvent database (ecoinvent 2003) too. From the available datasets the “transmission network, long-distance” was chosen. This study describes the environmental inventories for high voltage transmission for electricity trade in Europe.

Since there was only data for a transmission line averaged for Europe, the model was calculated for an storage output of one kWh and linearly applied to the results from WP 1 and WP 2. Data on the assumed losses was not given.

### Transmission line HVDC

The transmission line HVDC was modelled by using data from (Pehnt 2002). Pehnt refers to the inventory data for a transmission line (500 kV, 1.6 GW<sub>el</sub>) built from Borneo to Malaysia, based on data from Siemens and Fichtner (Germany). For this study these data were adopted to the conditions given by the results of WP 1 and WP 2 by scaling the load to 5 and 6 GW<sub>el</sub>, respectively, and by scaling to the lifetime of 30 years. Since Pehnt did not break up the inventory data into lines and periphery, it was assumed that the given data for “steel, high alloyed” and for “aluminium” referred to the lines only, the other data referred to the periphery. Consequently, “steel, high alloyed” and “aluminium” were scaled linearly up whereas the other data was not modified.

The model was calculated for a length of one km and linearly applied to the results from WP 1 and WP 2. Data on the assumed losses was not given.

## 6.3.2 Results

Table 100 shows the energy payback times for the terrestrial systems. They were calculated by adding the CED for the single components and applying formula 1. Considered were the systems with 0.5, 5, 10, 100, and 150 GW as given in the referred work packages. Intermediate results are shown in addendum 8.3.1

Table 100. Energy payback times of base-load and peak-load scenarios for the terrestrial systems

| <b>Base-load</b> | <b>Scenario period</b> | <b>GW</b> | <b>0.5</b> | <b>5</b> | <b>10</b> | <b>100</b> | <b>150</b> |
|------------------|------------------------|-----------|------------|----------|-----------|------------|------------|
| Photovoltaics    | 2010                   | months    | 28.7       | 32.4     | 31.9      | 32.0       | 32.6       |
| Solar Thermal    | 2010                   | months    | 8.4        | 8.9      | 9.4       | 9.4        | 9.2        |
| Photovoltaics    | 2030                   | months    | 8.2        | 9.2      | 8.2       | 8.3        | 8.5        |
| Solar Thermal    | 2030                   | months    | 7.7        | 8.3      | 8.9       | 8.1        | 8.2        |
| Photovoltaics    | 2030 dynamic           | months    | 8.2        | 9.2      | 8.2       | 8.3        | 8.5        |
| Solar Thermal    | 2030 dynamic           | months    | 6.8        | 7.4      | 8.0       | 7.3        | 7.4        |
| <b>Peak-load</b> | <b>Scenario period</b> | <b>GW</b> | <b>0.5</b> | <b>5</b> | <b>10</b> | <b>100</b> | <b>150</b> |
| Photovoltaics    | 2010                   | months    |            | 38.2     | 37.7      | 40.5       | 40.5       |
| Solar Thermal    | 2010                   | months    |            | 12.3     | 12.3      | 12.3       | 12.3       |
| Photovoltaics    | 2030                   | months    |            | 10.1     | 9.9       | 10.4       | 10.5       |
| Solar Thermal    | 2030                   | months    |            | 12.9     | 11.1      | 11.1       | 11.1       |
| Photovoltaics    | 2030 dynamic           | months    |            | 10.1     | 9.9       | 10.4       | 10.5       |
| Solar Thermal    | 2030 dynamic           | months    |            | 11.9     | 9.9       | 10.0       | 10.0       |

The following results can be drawn:

- For both systems, the energy payback times are strongly depending on the scenario period. The better the assumptions, the better the energy pay back times.

- o In case of *solar thermal systems*, the results are influenced through a better efficiency and less thermal storage in 2030.
- o In case of *photovoltaics* the results are influenced through a changeover to a different technology in 2030 (a-Si multi-junction cells).
- o In a similar way as shown in Figure 98 for the CED, the following figure shows the dynamic development of the EPT (only for the case of the 100 GW scenarios).

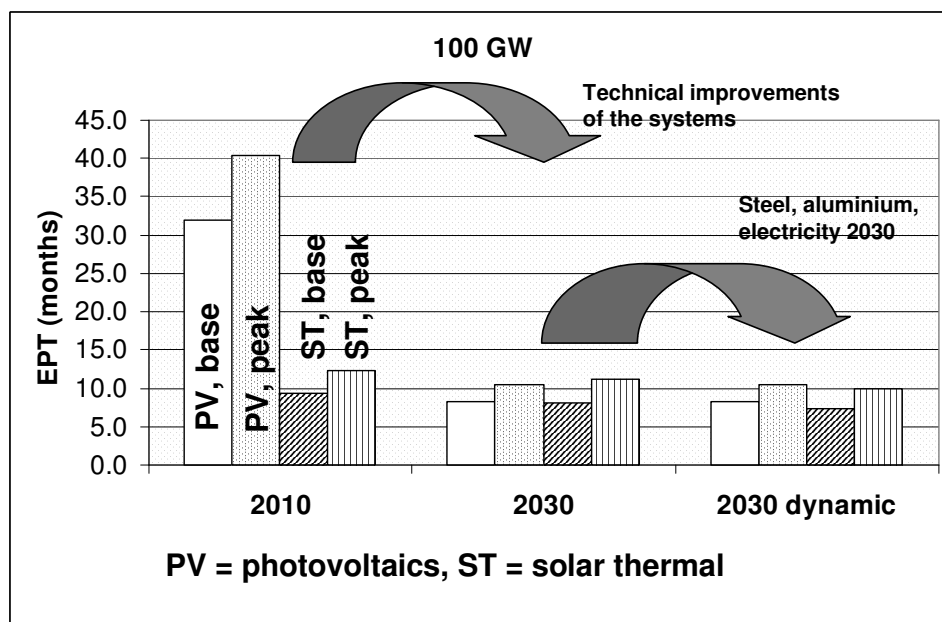


Figure 102 Dynamical improvements of the energy payback time (EPT), only for 100 GW

- o For *both systems*, the results within one period do not fluctuate very much.
  - o For the *solar thermal* base-load scenarios, the fluctuation within one period is caused mainly through the different length of the transmission lines (HVDC). The length of the lines increases superproportional to the load. This results in an increasing share of the HVDC on the total CED (and therefore on the EPT), as Table 101 shows by way of the “base-load, 2010” scenario. In contrary, for the peak-load scenarios there is a linear increasing of the lines’ length.
  - o In case of the *photovoltaics* base-load scenarios, there is only a little increase of the EBT. In fact, the length of the HVDC lines are increasing superproportional too. Because of the higher share of the photovoltaic system, this does not influence the total result very strongly.

Table 101. Shares of CED on the terrestrial systems' components (base-load, "2010")

| <b>Photovoltaics</b>      | <b>GW</b> | <b>0.5</b> | <b>5</b> | <b>10</b> | <b>100</b> | <b>150</b> |
|---------------------------|-----------|------------|----------|-----------|------------|------------|
| Photovoltaic power plant  | %         | 99.9       | 97.6     | 97.5      | 97.5       | 97.4       |
| Lines to storage (HVAC)   | %         | 0.0        | 0.0      | 0.0       | 0.0        | 0.0        |
| Storage                   | %         | 0.1        | 0.1      | 0.1       | 0.1        | 0.1        |
| Transmission lines (HVDC) | %         | 0.0        | 2.3      | 2.4       | 2.3        | 2.5        |

| <b>Solar Thermal Power</b> | <b>GW</b> | <b>0.5</b> | <b>5</b> | <b>10</b> | <b>100</b> | <b>150</b> |
|----------------------------|-----------|------------|----------|-----------|------------|------------|
| Solar thermal power plant  | %         | 99.8       | 96.6     | 92.5      | 89.3       | 88.7       |
| Lines to storage (HVAC)    | %         | 0.0        | 0.0      | 0.0       | 0.0        | 0.0        |
| Storage                    | %         | 0.2        | 0.2      | 0.2       | 0.1        | 0.2        |
| Transmission lines (HVDC)  | %         | 0.0        | 3.2      | 7.4       | 10.6       | 11.1       |

- o The energy payback times of the *solar thermal peak-load* scenarios are 24% to 61% higher than the results for the base-load scenarios (Table 100). This is caused by a much higher electricity generation from which a high amount gets lost as "excess generation". But this share is not accounted for the calculation of the EPT. Additionally, the length of the HVDC lines increases very much, which results in a lines' share of 17% to 33% of the total EPT, compared with a range from 3% to 14% within the base-load scenarios (see addendum 8.3.1).
- o Similar, the EPT of the *photovoltaics peak-load* scenarios are 9% to 26% higher than those for the base-load scenarios.
- o Figure 103 compares all scenarios for one selected load (100 GW, "2010") and shows the shares of the different components.

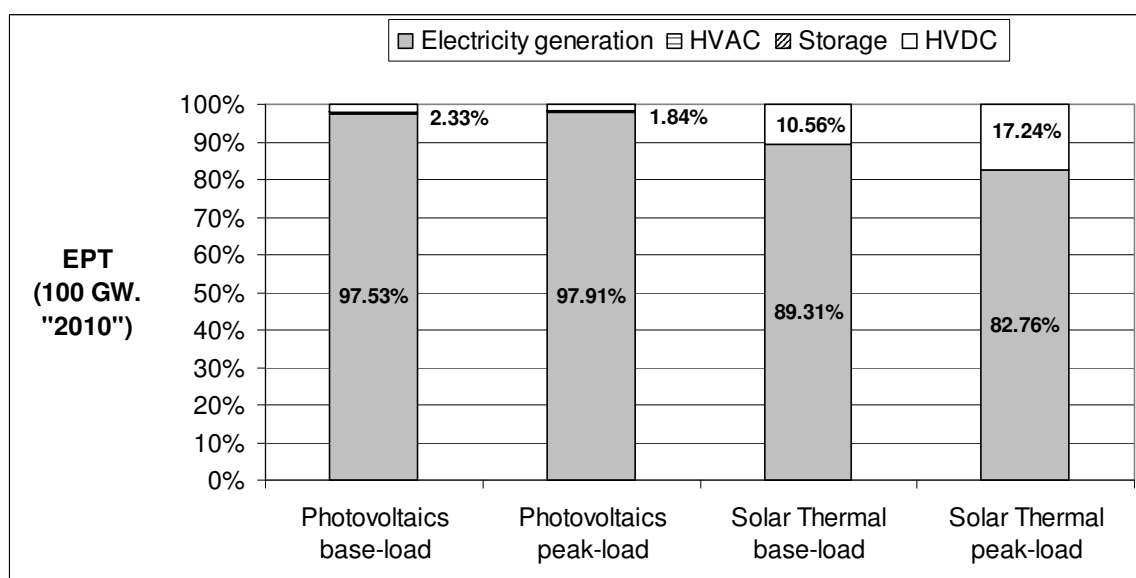


Figure 103. Shares of EPT on the terrestrial systems' components (100 GW)

- o Last but not least, in case of "2010", the energy payback times of *photovoltaics* are about 3.5 times higher than those of the *solar thermal electricity generation*. For future systems, photovoltaics is only 1.1 times worse than solar thermal.

## 6.4 Comparison and Viability Analysis

### 6.4.1 Results

Table 102 gives a comparison of the energy payback times for both, the space and the terrestrial systems. Only the systems for 10 and 100 GW base-load were considered because they are the only ones calculated for both systems concurrently.

Table 102. Energy payback times of all scenarios (base-load)

| Base-load     | Scenario period | GW     | 0.5 | 5 | 10   | 100  | 150 |
|---------------|-----------------|--------|-----|---|------|------|-----|
| Photovoltaics | 2010            | months |     |   | 31.9 | 32.0 |     |
| Solar Thermal | 2010            | months |     |   | 9.4  | 9.4  |     |
| Space         | 2010            | months |     |   | ---  | ---  |     |
| Photovoltaics | 2030            | months |     |   | 8.2  | 8.3  |     |
| Solar Thermal | 2030            | months |     |   | 8.9  | 8.1  |     |
| Space         | 2030            | months |     |   | 4.4  | 3.9  |     |
| Photovoltaics | 2030 dynamic    | months |     |   | 8.2  | 8.3  |     |
| Solar Thermal | 2030 dynamic    | months |     |   | 8.0  | 7.3  |     |
| Space         | 2030 dynamic    | months |     |   | 4.2  | 3.7  |     |

The following conclusions can be drawn:

- o It is clearly visible that the EPT of the space systems are much lower than those of the terrestrial systems. In case of the 10 GW scenario its EPT accounts for 50% to 54%, whereas in case of the 100 GW it accounts for 45% to 53% compared with the terrestrial systems.
- o The difference between terrestrial and space systems is caused mainly by the co-use of the ground PV for daylight as well as for laser beam. Whereas for the 10 GW base-load *terrestrial PV system* 55 GW<sub>p</sub> installed PV is required, the same dimensioned *space system* requires only 11 GW<sub>p</sub> installed PV. Additionally, a high efficiency of 50% for ground PV transferring the laser beam into DC intensifies this effect.
- o Again, the difference between 10 GW and 100 GW is caused by the delay in the scaling of the numbers of ground PV as mentioned above.

### 6.4.2 Constraints

Some constraints should be mentioned to be able to arrange the results in the right way:

- o Some difficulties arose regarding the calculation of the CED and the EPT of the *space-based systems*:
  - o A detailed description of the given scenarios was missing (building-up, operation and dismantling, system and components lifetime, etc.). Input and output parameters of the scenarios were not given in such a detailed matter as it was done by DLR 2004 for the terrestrial systems.
  - o The comparison could only be done regarding the base-load scenarios because no peak-load scenario was given for the space-systems.
  - o The sources of the mass and CED values given by EADS are not known and could not be reviewed.
  - o The data for dismantling the orbital system after 30 years are missing. Furthermore the construction of the essential starting platform and the buildings were neglected completely.
  - o The weight of the laser system as well as the given CED seems very low. An illustration of the assumptions made for the calculation of the laser system would have

been helpful as well as a comparison with other studies using laser systems for space systems (e.g. Klimke 2001, NASA 1993).

- o There are possible improvements of the *terrestrial systems*:
- o In contrary to the defaults given in DLR 2004, the solar thermal system SEGS was modelled by using thermal concrete slab storage instead of a two tank molten salt storage. No data was available and a request for data at the company Flagsol constructing such storages for a DSG plant has not been successfully. Since a molten salt storage requires much less energy for the construction than a concrete slab storage, the CED will be lower than calculated.
- o At the time a solar thermal system working with water steam instead of thermo oil is developed (direct steam generation, DSG). An actual comparison of the SEGS plant with the DSG plant shows a much better efficiency because of lower energetically requirements. The EPT of the investigated plants decreased from 4.5 months (SEGS) to 2.7 months (DSG). (INDITEP 2004).

### 6.4.3 Conclusions

Finally, the following conclusions can be drawn:

- o Considering the results shown in this study, the energy payback time of space systems are favourable over terrestrial systems.
- o Regarding the optimistic assumptions within the space scenarios and the possible improvements of the solar thermal systems, the CED and therefore the EPT given in the previous chapters could change: It is expected that the EPT of the terrestrial systems will decrease whereas the EPT of the space-based systems will increase.
- o It should be kept in mind that this study shows only the energy demands of the considered systems. To consider all environmental impacts, a complete life cycle assessment (LCA) especially for the space-base systems is suggested.



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## 7 Conclusions

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In this study a comparison has been made on energetic and economical aspects between terrestrial solar power concepts and space power concepts. Issues like environmental impact, safety, reliability and social acceptance were not part of the study.

The main conclusion is that space power concepts will not be competitive to terrestrial systems for at least the next twenty years. Whether such space concepts may become competitive after this period depends largely on the technological progress made, especially in the area of launching, robotics in space, power to laser/microwave conversion, re-conversion and heat rejection from space elements.

The technological requirements between terrestrial and space systems differ considerably. Whereas terrestrial systems are mainly based on established and proven relatively low-tech technology, space systems require the development of new or improved high-tech technology. In 2002 about one GW of terrestrial photovoltaic had been installed commercially worldwide, but to date no commercial or demonstration projects for space energy systems have been developed. As a result, information on a firm level for space systems is therefore much less available than for terrestrial systems.

From an economic point of view, one of the most critical factors for space systems are the launch costs. Also laser or microwave technology, power transmission and power conversion technology include critical issues to be resolved before space systems can be implemented.

### **Based on the findings in this study, the main conclusions are:**

- At least for the next twenty years, space systems will not be economically competitive to terrestrial systems even when optimistic assumptions are made regarding technology development and cost reductions for space components.
- When applied on a large-scale and in twenty to thirty years from now, power from photovoltaic and solar thermal systems may become competitive to conventional fossil fuels power.
- Cost estimates for space systems are highly uncertain due to the current immaturity of the technology: so far some required technology does not exist and has to be developed. There remains a certain risk that the technology's development towards maturity will take longer than anticipated or prove unworkable. Furthermore, the probability that the costs are substantially greater than those estimated in this study is high.
- Costs for the intermediate storage of power are high. This concerns all terrestrial photovoltaic generation methods. However, the need for storage should decrease when a broad mix of (renewable) energy is implemented within the whole supply zone. Over and above, further installation of additional renewable energies will go on within the supply zone.
- Less storage capacity is required for space systems based on microwave technology: space systems based on laser transmission technology still require (some more) storage capacity as the appearance of cloudy skies may interrupt delivery of electricity at any hour of the day, but need considerably smaller ground receivers.
- Implementation of smaller-scale terrestrial plants in Europe instead of large-scale plants in Africa reduces the vulnerability of the system and reduces the need for long-distance high

voltage lines. The implementation of such systems most likely increases costs, due to higher land costs, higher labour costs and reduced quantity and quality of irradiation.

- o Launch costs are the major cost item for space systems and need to be reduced to less than 50 to 100 €/kg before space power systems can be competitive to terrestrial systems.
- o Space systems need very high initial investment costs. The estimated cost of a 10 GW facility amounts to a hundred billion Euros.
- o The set-up of a space system is only reasonable for large capacities. A space system would largely profit when it is installed on a global scale. Application of small capacities is economically not interesting.
- o Terrestrial systems can be implemented gradually and the uncertainty in cost estimates is low compared to space systems.
- o There are no major launching activities foreseen in the near future. To obtain cost reduction in launching needs therefore large commitment to implement space power systems.
- o Energy payback times in future terrestrial and space concepts are low and amount to less than one year.
- o Increased knowledge is required concerning the impact of enhanced radiation in and around terrestrial receiver sites and on the effects of long high voltage transmission lines on biological species and humans.

#### **Based on this study we recommend**

- o to draw up a list of technical and economical bottlenecks and repeat this exercise in five to ten years from now if new information becomes available,
- o to reduce uncertainty in technology and costs for launching, lasers and other space-related technology,
- o to start field tests aimed at improving the technology (laser, in space construction),
- o to develop strategies for dismantling space systems,
- o to extend the analysis to a more 'realistic' scenario by better integration of a portfolio of energy supply technologies and integration into a more globally-oriented energy supply,
- o to make a complete life cycle assessment (LCA) especially for the space-based systems,
- o make a comparison of an integrated space-terrestrial scenario as the use of terrestrial renewables has just started, but will go on. Thus, a space-alone scenario will probably not be realistic,
- o to perform risk analysis
  - a. to loss of load,
  - b. to sudden and unexpected losses of high power capacities,
  - c. to possible (military) misuse or malfunction of the technology and space installations,
  - d. to health and biological effects of irradiation from space energy systems,
- o not to forget a sustainable inquiry about the public's acceptance,
- o to strengthen all efforts for a fast and global market introduction of the described terrestrial systems. Since the foreseen space systems are not working without the ground PV, the market introduction especially of the terrestrial PV systems is an overall precondition for the space systems, too.

Based on current electricity use and available projections on growth rates, it is estimated that the annual base load of the regarded zone in the period 2020 and 2030 is about 4000 to 4500 TWh.

## 7.1 Conclusions on terrestrial concepts

To keep comparability to the space system, only solar driven terrestrial power plants have been taken into account. Provisional estimates indicate that the large-scale implementation of photovoltaic or solar thermal power plants in North Africa is the most cost-effective. Analyses show that more than sufficient land is available to install the required capacities. Analyses also show that pumped hydroelectricity is a more energy efficient and cost-effective storage medium than hydrogen storage when land availability is not an issue and pumped hydroelectricity is applicable. High voltage DC transmission lines of a capacity of 5 respectively 6.5 GW are able to transport the generated electricity to Europe. Transmission losses are between eighteen and fourteen percent, and average transmission costs (between about 5 to 200 € per MWh) depend strongly on the chosen scenario. Depending on the scenario, a certain percentage of the electricity needs to be dumped or sold at different conditions.

### 7.1.1 *Terrestrial photovoltaic*

Over the last decades, photovoltaic technologies show a relatively constant cost reduction of eighteen to twenty percent for each doubling of capacity. It is expected that this cost reduction can be maintained in the mid-term by introducing new technologies. Large-scale introduction of photovoltaics may reduce current module costs from 4500 € per kW to 1500 € per kW or less. The need for (expensive) seasonal storage can be minimised when the photovoltaic cells are optimally oriented. Two different tilt angles of 60° in winter and 10° in summer provide nearly a daily constant power production in North Africa.

About six and half times the base load demand of photovoltaic peak capacity is required. The levelised electricity costs using today's technology varies from 14 € per MWh for large-scale systems (1000 GW<sub>p</sub> installed, 150 GW<sub>e</sub> demand) to 28 € per MWh for relatively small-scale systems (3 GW<sub>p</sub> installed, 0.5 GW<sub>e</sub> demand). The energy payback times for all implementation levels are approximately two and half years. Implementation of future systems reduces the cost to 7 to 12 € per MWh and reduces the energy payback time to less than one year. Depending on the size of the implementation and the status of technology, about forty to fifty-five percent of costs are power generation costs. Storage and dumping costs are approximately thirty five to forty percent, and transmission costs five to fifteen percent. It is expected that substantial cost reductions can be established by the application of more (renewable) energy sources with different load characteristics. However, analysis of a mixture of renewable energy sources was outside the scope of this study.

### 7.1.2 *Solar thermal*

Solar thermal power plants are currently much less applied than PV. To date about 354 MW are installed. Due to the higher level of conventional equipment, such as steam turbines, the progress ratio is expected to be lower than for photovoltaics. Until the first 500 GW will be installed, a cost reduction rate of about twelve percent per doubling of installed capacity is assumed; thereafter, the cost reduction is assumed to continue by four percent for each doubling of installed capacity. Solar thermal peak capacity requires about one and half times the base load to cover demand. Due to temporal onsite storage facilities, considerable less installed peak capacity is required compared to photovoltaic system.

The levelised electricity costs using today's technology varies from 6 € per MWh for large-scale systems (220 GW<sub>p</sub> installed, 150 GW<sub>e</sub> demand) to 14 € per MWh for relatively small-scale systems (0.75 GW<sub>p</sub> installed, 0.5 GW<sub>e</sub> demand). The energy payback times for all implementation levels are less than one year. Implementation of future systems reduces the costs slightly to 5 to 10 € per MWh

and reduces the energy payback time by approximately two months. Depending on the size of the implementation and the status of the technology, about sixty-five to seventy percent of costs are power generation costs (including onsite storage). External storage and dumping costs are much lower compared to photovoltaic systems, and amounts to approximately ten to fifteen percent with transmission costs equating to ten to twenty percent.

## 7.2 Conclusion on solar energy system in space

Terrestrial solar systems suffer from alternating supply between day and night, winter and summer and from cloudy skies. This drawback can largely be overcome by solar energy systems in space. In addition, space systems can in principle shift supply to where power is needed. Due to the high initial investment costs, space systems may become attractive only for implementation on a global scale. For space systems, huge lightweight photovoltaic panels are placed in low or geostationary earth orbits, which transmit collected energy to a receiver on earth via a microwave or laser beam. In contrast with terrestrial systems, so far no such installations have been installed in space. Considerable technological breakthroughs are required to be able to implement such space power concepts. Projected energy efficiencies and costs figures are therefore much less firm than those for terrestrial systems. Important issues are transportation to space, conversion efficiencies to laser, heat rejection in space, and wireless transfer of energy.

Current earth to orbit transportation costs by Ariane 5 amounts to about 10,000 €/kg. Cumulated annual transported mass is about 500 tonnes. Large-scale implementation of solar energy systems will require a many-fold increase in capacity, and a complete new generation of rockets will need to be developed with important features such as the reuse of fuel tanks, payload shrouds, cryo-insulation and the utilisation of rockets reusable avionics reentry module. One space power system with an output of ten GW requires 1,780 (Adler-type) to 10,330 (Ariane 5+-type) launches.

When transmission via lasers is applied, the terrestrial photovoltaic receiver site will simultaneously to the laser also convert natural daylight into power in addition to what is supplied by the laser. The benefit of co-generation is relatively small and the 'extra' production of photovoltaics by the conversion of daylight into electricity amounts to about fifteen percent. Optimising the photovoltaic angle for daylight instead of the laser beam enhances this percentage. However, in this case the total output of power decreases dramatically.

The levelised electricity costs for space energy systems amount to 9 € per MWh for large-scale applications (1705 GW<sub>p</sub> in space; 220 GW<sub>p</sub> on ground). In this concept, the transmission and storage costs are relatively small and comprise about twenty and sixteen percent of the costs respectively. The levelised electricity costs are highly sensitive to launch costs. Five times higher launch costs result in a three times higher electricity costs, i.e. about 30 € per MWh. Adding more terrestrial photovoltaic can reduce the levelised electricity costs. However, from a cost point of view, the optimal mix is pure terrestrial without any space components. The more ground receivers available, the more flexible the space-terrestrial system becomes, i.e. one can choose to direct the laser beam to supply the energy to where its demand is the greatest, although this increased flexibility increases production costs by three to eighteen percent.

Despite the energy-intensive launch activities, the energy payback time for a space power system is small and amounts to about four months. This low number can mainly be explained by the lightweight PV structure in space and the significantly lower peak PV capacity in complete and especially on ground due to its high efficiency for laser light and the lower over-seizing due to less storage needs.

## 8 Appendix

### 8.1 Detailed Information for the Space Power Systems

#### 8.1.1 A. NASA SPS systems data

A-1 Main Solar Power Reference Concepts Characteristics

| TECHNOLOGIES                                                              | SPS CONCEPTS                           | PERFORMANCE/COST OBJECTIVES                                                          | SYSTEM COST GOALS                                            | ARCHIITECTURE COST GOAL                                                                                                                                                                |
|---------------------------------------------------------------------------|----------------------------------------|--------------------------------------------------------------------------------------|--------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| -Mass Productable Systems<br>-Highly Modular Systems                      | <i>SUN</i><br><br><i>TOWER</i>         | SSP Platform Systems<br>~300-350/kg                                                  | SPS<br>POWER<br>SYSTEMS<br><br>< 1 cent/kWh                  | <i>GOAL</i><br><br><i>Enabling of Large-Scale Commercially-Viable Solar Power in Space For Terrestrial and Space Markets</i><br><br><i>SPS BASELOAD POWER for Less than 5 Cent/kWh</i> |
| -HTS Power Cables<br>-Rigidized Hoyt Tether<br>I-ntelligt. Modul. Systems |                                        | SSP Platform Systems<br>< 4-6 kg/kW                                                  |                                                              |                                                                                                                                                                                        |
| -> 35 % Efficiency PV<br>-Thin Film Structures                            |                                        | ~1-2 MW PV Solar Arrays<br>< 2-3 kg/kW<br>~ 1-2 MW Solar Array<br><~\$1000-\$1500/kW |                                                              |                                                                                                                                                                                        |
| -Mass Producible Arrays<br>-Highly Modular Systems                        | <i>CONSTELLATION</i><br><br><i>SPS</i> | In-Space Transport<br>300-400 \$/kg                                                  | SPACE SOLAR<br>SYSTEMS<br>INSTALLATION<br><br>< 2,5 Cent/kWh |                                                                                                                                                                                        |
| -High Efficiency Solar Electric Propulsion                                |                                        | ETO Transport<br>\$400/kg                                                            |                                                              |                                                                                                                                                                                        |
| High Ops Perform. Margins<br>Highly Reusable Vehicles                     |                                        | Ground Assembly Person.<br>1/MW                                                      |                                                              |                                                                                                                                                                                        |
| Robotic/Self-Assembly<br>Automatic. RVD                                   |                                        | WPT Transmitter/Array<br><\$1500-\$1700/kW                                           | END-TO-END<br>WIRELESS<br>POWER<br>TRANSMISSION              |                                                                                                                                                                                        |
| Low-Cost Phase Shifters<br>Highly Modular Systems                         | <i>SANDWICH</i>                        | WPT Transmitter Array<br>< 2-2.5 kg/kW                                               |                                                              |                                                                                                                                                                                        |

|                                                       |                                                          |                                                 |                                                           |  |
|-------------------------------------------------------|----------------------------------------------------------|-------------------------------------------------|-----------------------------------------------------------|--|
| Low-Mass Phased Array Sub-Arrays                      | <i>SPS</i>                                               |                                                 | <1 Cent/kWh                                               |  |
| High-Efficiency Components<br>High Temp./Thermal Mgmt |                                                          | End-to-End WPT Efficiency<br>> 30-40 %          |                                                           |  |
| High Efficiency Rectenna<br>Fail-Safe Beam Control    | <i>3-AXIS</i><br><br><i>STABILIZED</i><br><br><i>SPS</i> | RF Rectenna Construction<br>< \$1,5/W Delivered | RECURRING OPS &<br>MAINTENANCE COST<br><br>< 0,5 Cent/kWh |  |
| Autonomous Operations<br>Robust/Learning Machines     |                                                          | Ground Ops Personnel<br>1/MW                    |                                                           |  |
| Low Cost 100 MW-Hr Energy Storage                     |                                                          | Ground Energy Storage<br>< \$20/kWh             |                                                           |  |
| Debris-Impact Tolerance<br>5-10% H/W Refurb./10 Years |                                                          | Overall System Livetime<br>40 Years             |                                                           |  |

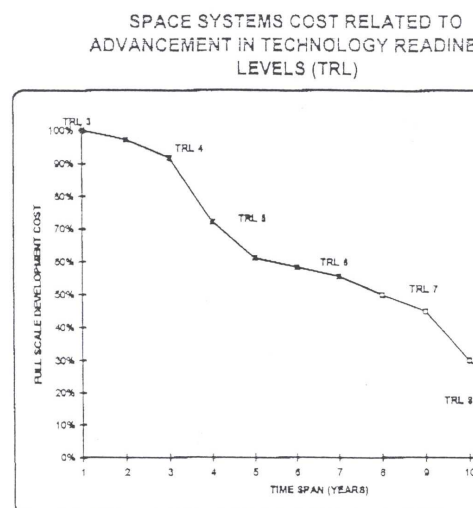
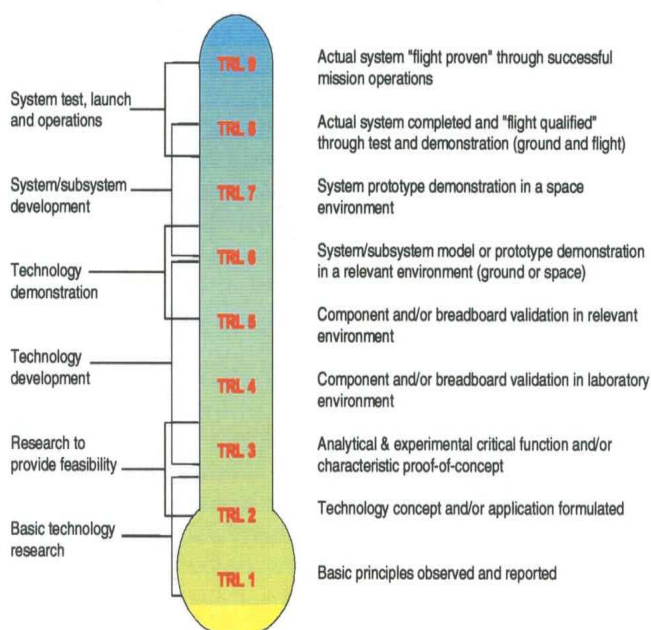
## A-2 Main Solar Power Reference Concepts Characteristics - Structural Aspects

| TECHNOLOGIES                                      | SPS CONCEPTS<br><i>Structures,<br/>Materials &amp;<br/>Controls</i> | PERFORMANCE/COST<br>OBJECTIVES                      | SYSTEM<br>COST GOALS                         | ARCHIITECTURE<br>COST GOAL                                                                                                                                                                      |
|---------------------------------------------------|---------------------------------------------------------------------|-----------------------------------------------------|----------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| -Large Lightweight<br>Deployable<br>Structures    | <b>DEPLOYABLE/<br/>INFLATABLE<br/>SOLAR ARRAYS</b>                  | Packaging Efficiency > 50<br>Mass/Area < 0.37 kg/m2 | Solar Power<br>Generation<br><br>< 1.2 kg/kW | <b>GOAL</b><br><br><i>Enabling of<br/>Light, Flexible<br/>And<br/>Low Specific-Mass<br/>Structures for<br/>Large, Long-life<br/>Space Solar Power<br/>Systems</i><br><br><b>Primary<br/>SSP</b> |
| -Solar Concentrators                              |                                                                     | Connection Ratio<br>> 15:1                          |                                              |                                                                                                                                                                                                 |
| -Distributed Control                              |                                                                     | Pointing Accuracy<br>< +/- 3 deg                    |                                              |                                                                                                                                                                                                 |
| -Long-life Materials                              | <b>DEPLOYABLE<br/>POWER<br/>BACKBONE</b>                            | Operational Lifetime<br>> 15 yrs                    | Power<br>Distribution<br><br>< 0.12 kg/kW    |                                                                                                                                                                                                 |
| -Lightweight<br>Deployable Power<br>Concentrators |                                                                     | Packaging Efficiency > 10<br>Mass/Length < 0.15 g/m |                                              |                                                                                                                                                                                                 |
| -Power/Structural<br>Connections                  |                                                                     | Reliability<br>> 0.9999                             |                                              |                                                                                                                                                                                                 |
| -Autonomous RVD                                   |                                                                     | Reliability<br>> 0.9999                             |                                              |                                                                                                                                                                                                 |



|                                          |                                     |                                                  |                             |                                              |
|------------------------------------------|-------------------------------------|--------------------------------------------------|-----------------------------|----------------------------------------------|
| -Integrated Structure/Power Distribution | <b>MODULAR TRANSMITTING ANTENNA</b> | Mass/Area < 50kg/m2                              | Wireless Power Transmission | <b>Structures A Less than &lt; 3-4 kg/kW</b> |
| -Autonomous Modular Assembly             |                                     | Positional Accuracy < 0.01 m                     |                             |                                              |
| - Efficient Thermal Mgmt                 |                                     | Heat Rejection structures > 0.20 kW/kg (thermal) |                             |                                              |

A-3 The Technology Readiness Level, TRL, as defined and used by NASA shall also be applied in ASTRA to identify/quantify technology gaps and cost and risk of a potential development



**NASA TECHNOLOGY READINESS LEVELS**

TRL 1: Basic principles observed and reported

TRL 2: Conceptual design formulated

TRL 3: Conceptual design tested analytically or experimentally

TRL 4: Critical functions and characteristics demonstrated

TRL 5: Component/Breadboard tested in relevant environment

TRL 6: Prototype/engineering model tested in relevant environment

TRL 7: Engineering model tested in space

TRL 8: "Flight-qualified" system

TRL 9: "Flight-proven" system

A-4 SPS Main Technologies Development Perspectives

| SSP Technology                          | Performance Metrics            |         |        | Current TRL | Projected R&D Effort |
|-----------------------------------------|--------------------------------|---------|--------|-------------|----------------------|
|                                         | Area                           | Current | Goal   |             |                      |
| Very Large Lightweight Structures       | Packaging Efficiency           | 20.1    | > 50.1 | 4           | III                  |
|                                         | Mass/Area (kg/m <sup>2</sup> ) | 2.4     | < 0.37 | 4           | III                  |
| Solar Concentrators                     | Concentration Ration           | 10.1    | 15.1   | 4           | III                  |
| Distributed Control                     | Pointing Accuracy (deg)        | 10      | < 3    | 2           | IV                   |
| Long-life Materials                     | Operational Life (yrs)         | 3       | 15     | 3           | II                   |
| Lightweight Deployable Power Conductors | Packaging Efficiency           | -       | > 10.1 | 1-2         | IV                   |
|                                         | Mass/Length (kg/m)             | -       | < 0.15 | 1-2         | IV                   |
| Power/Structural Connections            | Reliability                    | -       | 0.9999 | 2           | III                  |
| Autonomous RVD                          | Reliability                    | -       | 0.9999 | 5           | III                  |
| Integrated Structure/Power Distribution | Mass/Area (kg/m <sup>2</sup> ) | -       | < 50   | 2           | IV                   |
| Autonomous Modular Assembly             | Positioning Accuracy (m)       | -       | < 0.01 | 3           | IV                   |
| Surface Figure Control                  | Surface Accuracy (m)           | -       | < 0.01 | 1-2         | III                  |
| Efficient Thermal Mgmt                  | Heat Rejection (kW/kg)         | 0.04    | > 0.20 | 4           | III                  |

Identification of Potential Applications and Benefits:

- o Very large deployable structures for large apertures and solar cells
- o Ultra-lightweight solar arrays for Earth and space science missions
- o Distributed control of spacecraft formations
- o Tethers for power generations, transportation, and rotating systems

## 8.1.2 B. Selected results

### B-1 Basic Assumptions

#### Potential Energy Sources for SPI

##### 1. Solar electromagnetic radiation:

$$S_0 = 1371 \pm 5 \text{ [W/m}^2\text{]}$$

$$\lambda < 0.38 \text{ [\mu m]}: 7.003 \text{ [%]}$$

$$0.38 \text{ [\mu m]} < \lambda < 0.75 \text{ [\mu m]}: 44.688 \text{ [%]}$$

$$\lambda < 0.75 \text{ [\mu m]}: 48.309 \text{ [%]}$$

Radiation pressure at 100 % reflectivity:  $9.14 \text{ E-06 [N/m}^2\text{]}$

Variation with distance x from sun;

$$S_x = S_0 * (1 / x)^2 \text{ [W/m}^2\text{]}; p = p_0 * (1 / x)^2 \text{ x in AU; } 1 \text{ AU} = 150 \text{ E06 [km]}$$

Variation of distance a [AU] from Earth to a facility in a circular solar orbit at x [AU]:

$$\blacklozenge \text{ Venus orbit: } x \approx 2/3 \text{ [AU]}; S = 3085 \text{ [W/m}^2\text{]}; \rightarrow a_{\min} \approx 1/3 \text{ [AU.]; } a_{\max} \approx 5/3 \text{ [AU]}$$

$$\blacklozenge \text{ Mercury orbit: } x \approx 1/3 \text{ [AU]}; S = 12339 \text{ [W/m}^2\text{]}; \rightarrow a_{\min} \approx 2/3 \text{ [AU.]; } a_{\max} \approx 4/3 \text{ [AU]}$$

Insolation in inner solar orbits higher, but orbits are hardly accessible and require:

- o extremely long-range power transmission over hundreds of millions of kilometres
- o extremely advanced technologies (not at hand today and also not in near future)

**Conclusion:** Earth orbits, probably with concentration of sunlight are the right choice.  
Extraterrestrial inner solar orbits not reasonable

##### 2. Solar wind:

H and He ions and electrons; macroscopically electrically neutral

$$\approx 5 \text{ to } 10 \text{ ions per cm}^3 \text{ at } \approx 400 \text{ [km/sec]} \rightarrow (5 \text{ to } 10) \text{ E06 [ions/(m}^3 * \text{sec)]}$$

$$\rightarrow (2 \text{ to } 4) \text{ E12 [ions/(m}^2 * \text{sec)]}$$

$$\bullet \text{ Kinetic energy flux density: } \rightarrow (3 \text{ to } 6) \text{ E-04 [W/m}^2\text{]}$$

$$\bullet \text{ Electron / ion recombination: } \rightarrow (5 \text{ to } 10) \text{ E-06 [W/m}^2\text{]}$$

$$\bullet \text{ H and He3 fusion assuming 100\% efficiency: } \rightarrow 1 \text{ to } 2 \text{ [W/m}^2\text{]}$$

Density of power flux orders of magnitude lower than solar electromagnetic insolation

Large variations with solar activity (solar storms, solar bursts)

**Conclusions:** Utilisation of solar (and cosmic) particle radiation not reasonable

##### 3. Electromagnetic Tether and near Earth plasma in LEO:

Compensation of extra drag due to extraction of power demands thrust (and extra power)

Example: Ideal Electromagnetic Tether at 100 % efficiency

$$\blacklozenge \text{ Ideal voltage: } U_0 = B * L * v; \text{ Power: } P = U_0 * I;$$

$$\blacklozenge \text{ Drag force: } F = B * L * I \rightarrow F \geq P / v \quad (v = v_{\text{circular}}; \approx 7738 \text{ [m/sec]})$$

$$\blacklozenge \text{ Required propellant flow rate: } dm/dt = F / J_{sp}; \rightarrow dm/dt = P / v / J_{sp}$$

$$\text{Best chemical LH}_2\text{/LO}_2 \text{ propulsion } (J_{sp}: \approx 4500): \approx 0.10 \text{ [kg/kWh]}$$

$$\text{Electric propulsion } (J_{sp}: \approx 15000): \approx 0.03 \text{ [kg/kWh]} \text{ plus } \approx 0.36 \text{ [kW/kW]}$$

$$\text{Electric propulsion } (J_{sp}: \approx 41667): \approx 0.011 \text{ [kg/kWh]} \text{ plus } \approx 1.00 \text{ [kW/kW]}$$

**Conclusion:** Application not reasonable due to excessive propellant and / or power demand.

#### **4. He3 on Moon for clean fusion:**

He3 carried to the Moon with the solar wind over billions of years, stored in lunar regolith?

Harvesting of He3 requires large scale lunar surface mining and complex processing

He3 fusion more difficult than D / T fusion (twice the excitation energy)

**Conclusions:** If feasible, then better do it on Earth, since more efficient, simpler, less costly.

#### **5. Nuclear power plants in orbit:**

**Conclusions:** Overall efficiency, risks, cost, operability, and public acceptance questionable

Not recommended, but probably disposal of nuclear waste in space

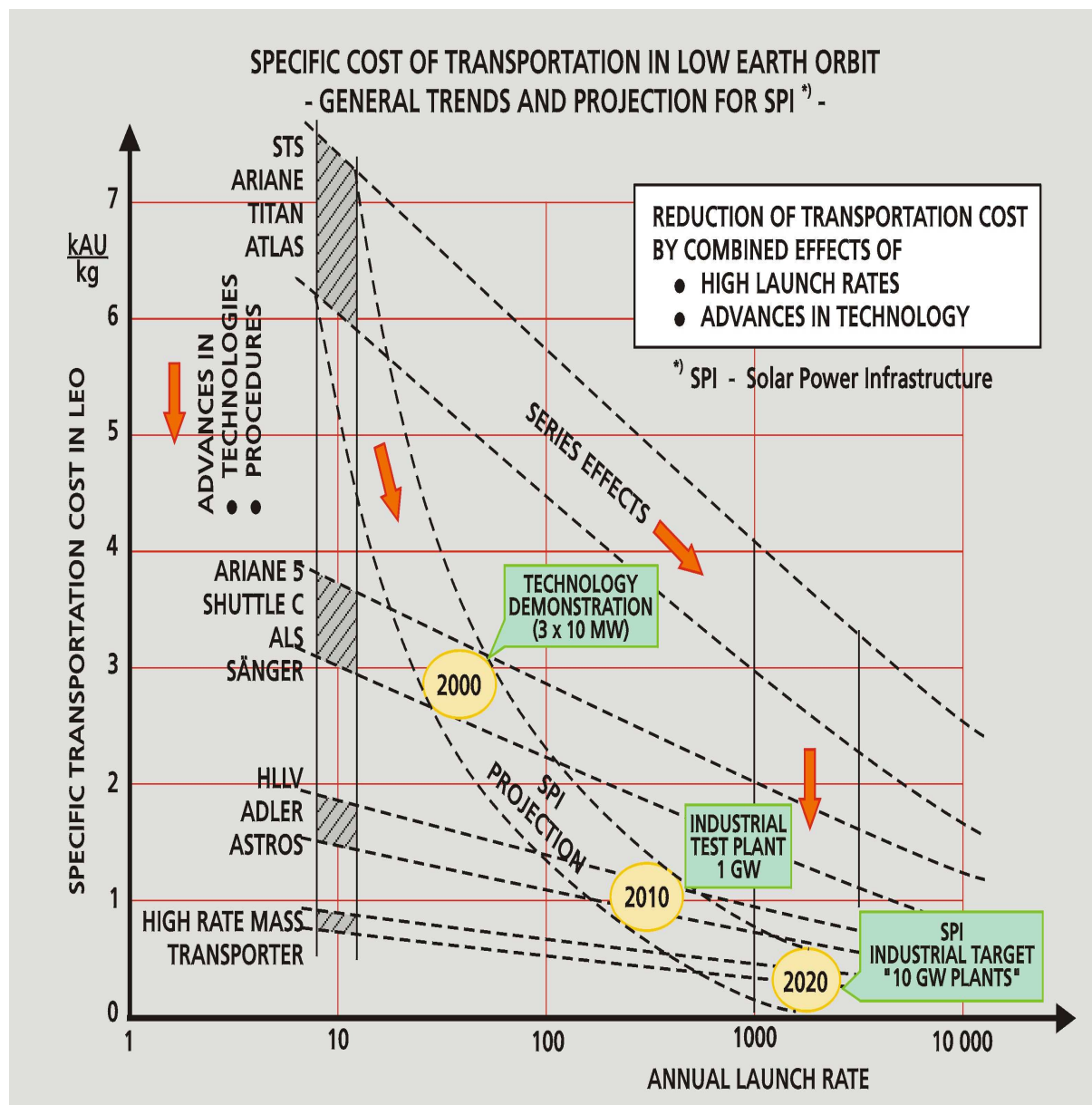
**General conclusion: Sunlight is the only inexhaustible, clean, safe energy source for SPI**

### **B-2 Space Solar Energy Generation for Earth Application - Efficiencies and Transport Cost**

| Time Horizont                            | Terrestrial   |             | Space        |             |
|------------------------------------------|---------------|-------------|--------------|-------------|
|                                          | Today         | Future      | Today        | Future      |
| <b>Energy Generation:</b>                |               |             |              |             |
| Photovoltaic Array                       | 0,14          | 0,22        | 0,13-0,22    | 0,22÷0,34   |
| Solar-thermal                            | 0,28          | 0,35        |              | 0,36        |
| Solar-Laser                              | (0,025; Test) | (0,05)      |              | 0,10        |
| <b>Energy Transmitter:</b>               |               |             |              |             |
| Microwave (2,35÷5,9 GHz)                 | 0,77÷0,60     |             |              | 0,85÷0,62   |
| Laser (≈ 0,8; 1,06; 5 μm)                | 0,20÷0,35     |             |              | 0,45÷0,60   |
| <b>Transmission &amp; Beam Reception</b> |               |             |              |             |
| Microwave                                |               | 0,96 x 0,83 |              |             |
| Laser                                    |               | 0,90 x 0,83 |              |             |
| <b>Electricity Re-Conversion:</b>        |               |             |              |             |
| Rectenna (Microwave)                     | 0,8           | 0,6÷0,8     |              |             |
| Photovoltaic Array (Laser)               | 0,48          | 0,4÷0,6     |              |             |
| Laser-thermal                            | (0,30)        | 0,5÷0,6     |              |             |
| <b>Energy Storage:</b>                   |               |             |              |             |
| Water Electrolysis                       | 0,8           | 0,85        |              |             |
| H <sub>2</sub> -Cavern Storage           | 0,96          | 0,96        |              |             |
| H <sub>2</sub> -Fuel Cells               | 0,65          | 0,75        |              |             |
| <b>Energy Transport:</b>                 |               |             |              |             |
| 3000km HVDC <sup>1)</sup>                | 0,92          | 0,94        |              |             |
| 3000km H <sub>2</sub> -Pipeline          | 0,90          | 0,92        |              |             |
|                                          |               |             |              |             |
| <b>Space Transport:</b>                  |               |             |              |             |
| Earth-LEO <sup>2)</sup>                  |               |             | k≈5000 \$/kg | k≤200 \$/kg |
| LEO-GEO <sup>3)</sup>                    |               |             | k≈5000 \$/kg | k≤ 50 \$/kg |

<sup>1)</sup> HVDC = High Voltage Direct Current Transmission; <sup>2)</sup> LEO = Low Earth Orbit; <sup>3)</sup> GEO = Geostationary Orbit

### B-3 Space Transport Cost Comparison



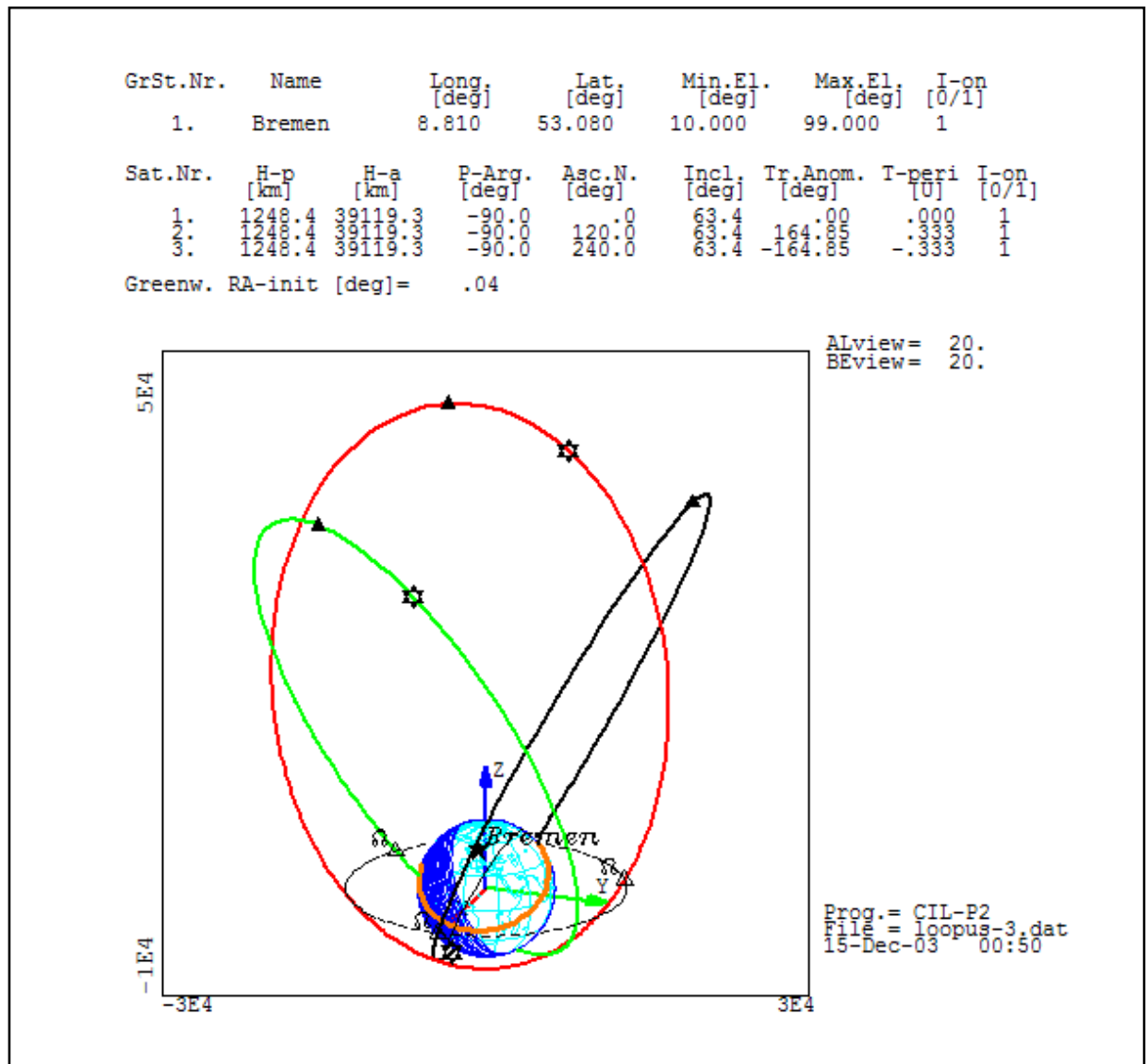
#### 8.1.3 C. SPS application scenarios - candidates orbits assessments

- C-1 Loopus - Type Orbits
- C-2 Sun-Synchronuos Orbits
- C-3 LEO Orbits

## C-1 Examples for LOOPUS-Constellations

## 3 Satellites, 2 Loops

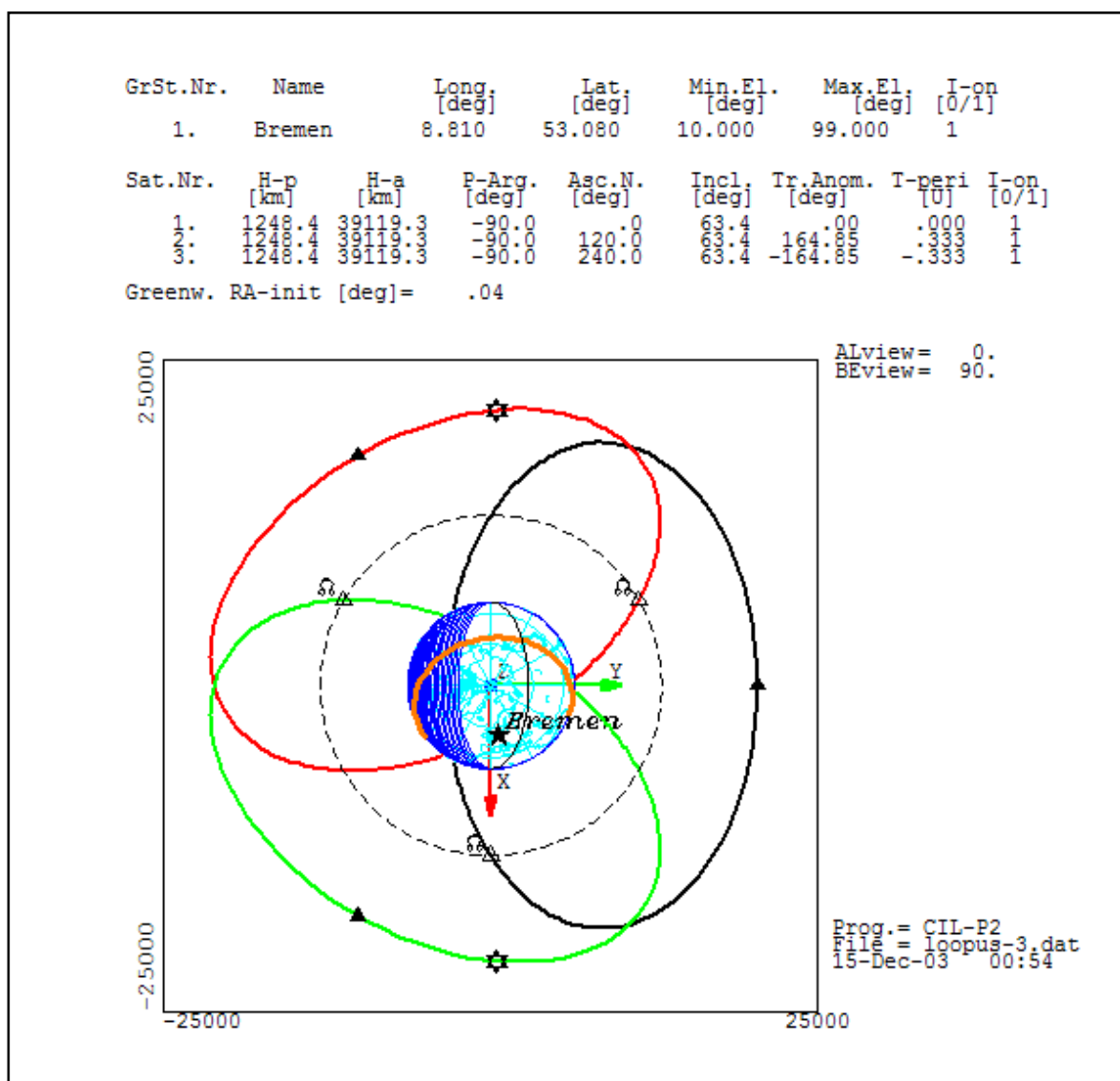
### 1.1 Inertial View, Perspective 1



LOOPUS-Constellation with 3 Satellites

Inertial View (geocentric, equatorial),  
Perspective 'flat' on Equator Plane

## 1.2 Inertial View, Perspective 2

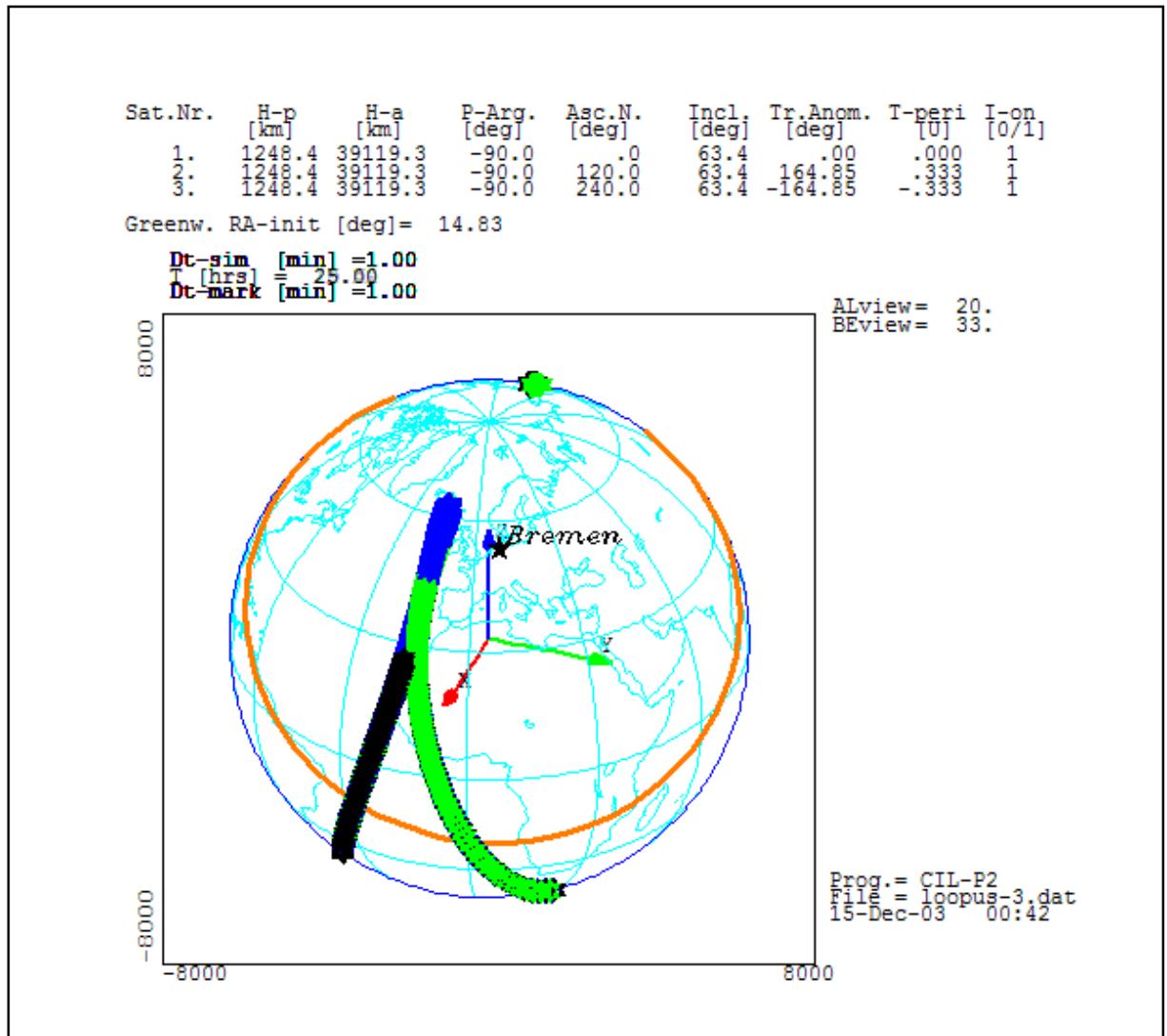


LOOPUS-Constellation with 3 Satellites

Inertial View (geocentric, equatorial),  
Perspective 'top' on Northpole



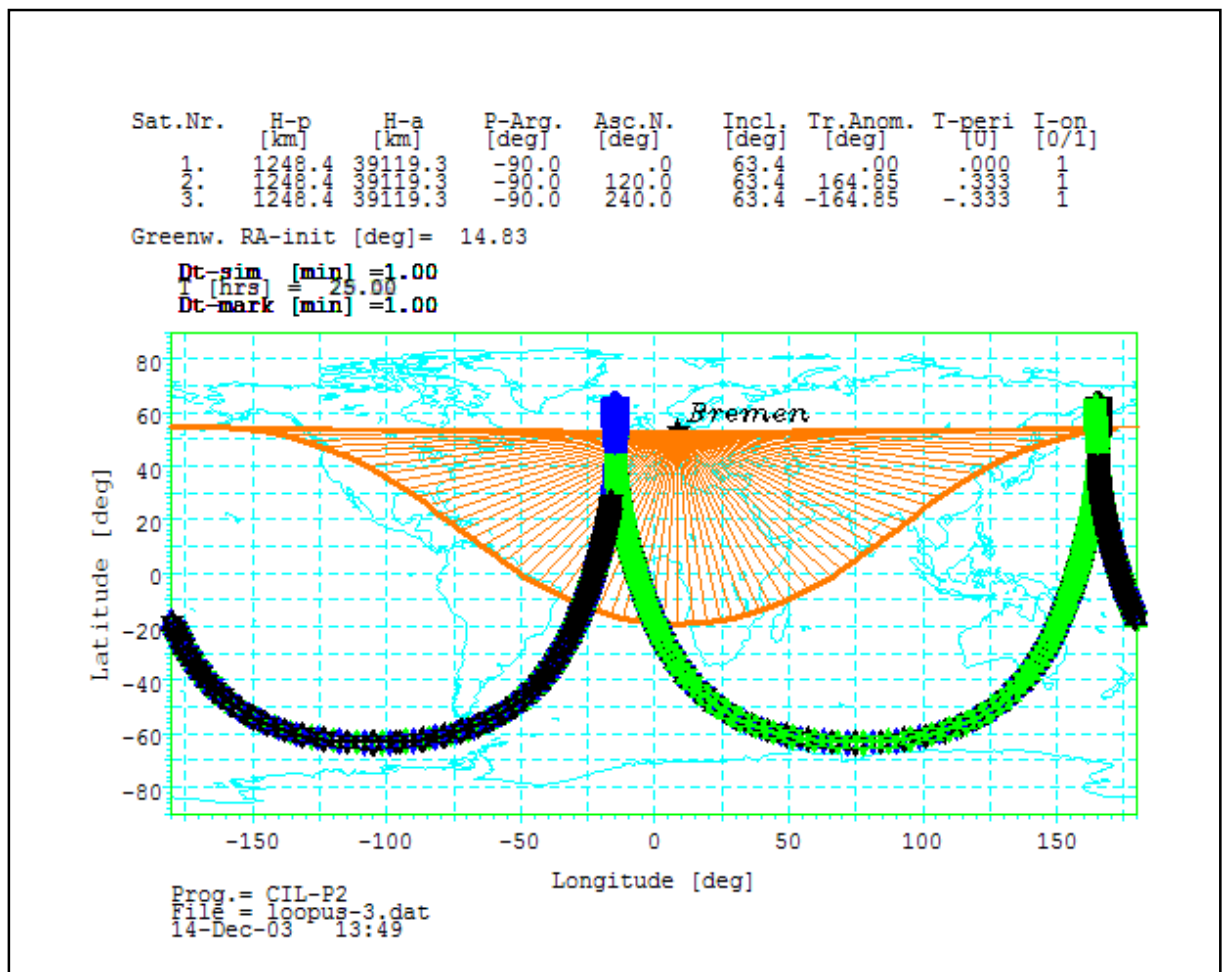
### 1.3 Groundtrack as Spherical Projection



LOOPUS-Constellation with 3 Satellites  
 generates a Groundtrack with 2 geostationary Loops  
 on the Northern Hemisphere

Diagram as Spherical Projection

## 1.4 Groundtrack as Rectangular Projection



### LOOPUS-Constellation with 3 Satellites

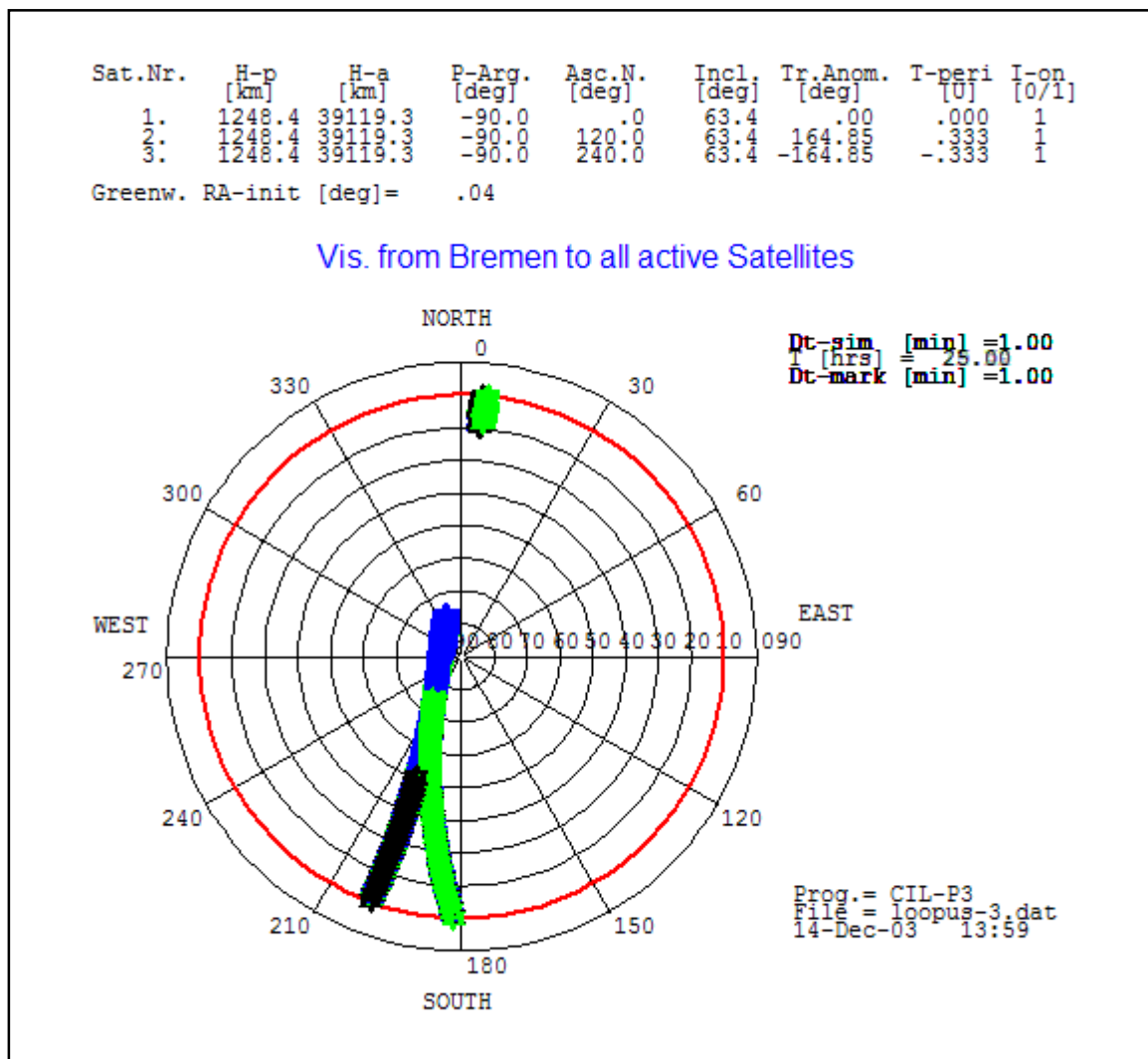
generates a Groundtrack with 2 geostationary Loops  
on the northern Hemisphere

Diagram as Rectangular Projection.

#### Remarks:

- The Groundtrack (Position of the Loops) can be adjusted liberately in East-West-Direction at the beginning by a respective holding time on a LEO Parking Orbit ('Phasing'), but remains unchanged afterwards in the operational mode
- At the Cross-point of the Loops a change of the satellite occurs (one 'rises', the other 'sets').
- This results in a quasi-stationary Ground Contact Status

## 1.5 Loops of the Perspective from Bremen

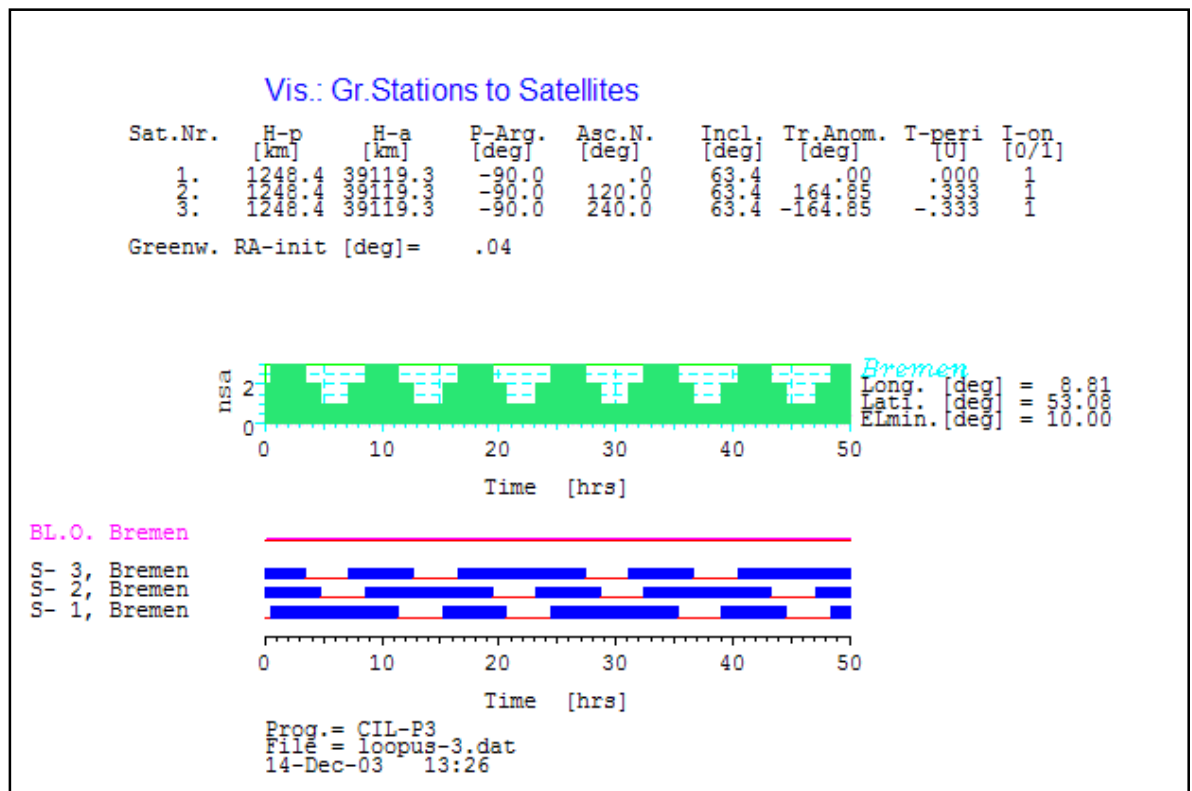


### LOOPUS-Constellation with 3 Satellites

generates 2 geostationary Groundtrack-Loops on the Northern Hemisphere  
Diagram in Polar Coordinates of the Perspective from Bremen.

As the Loops are occupied by a Satellite continuously a quasi-stationary Contact is Provided

## 1.6 Contact Timelines to Bremen



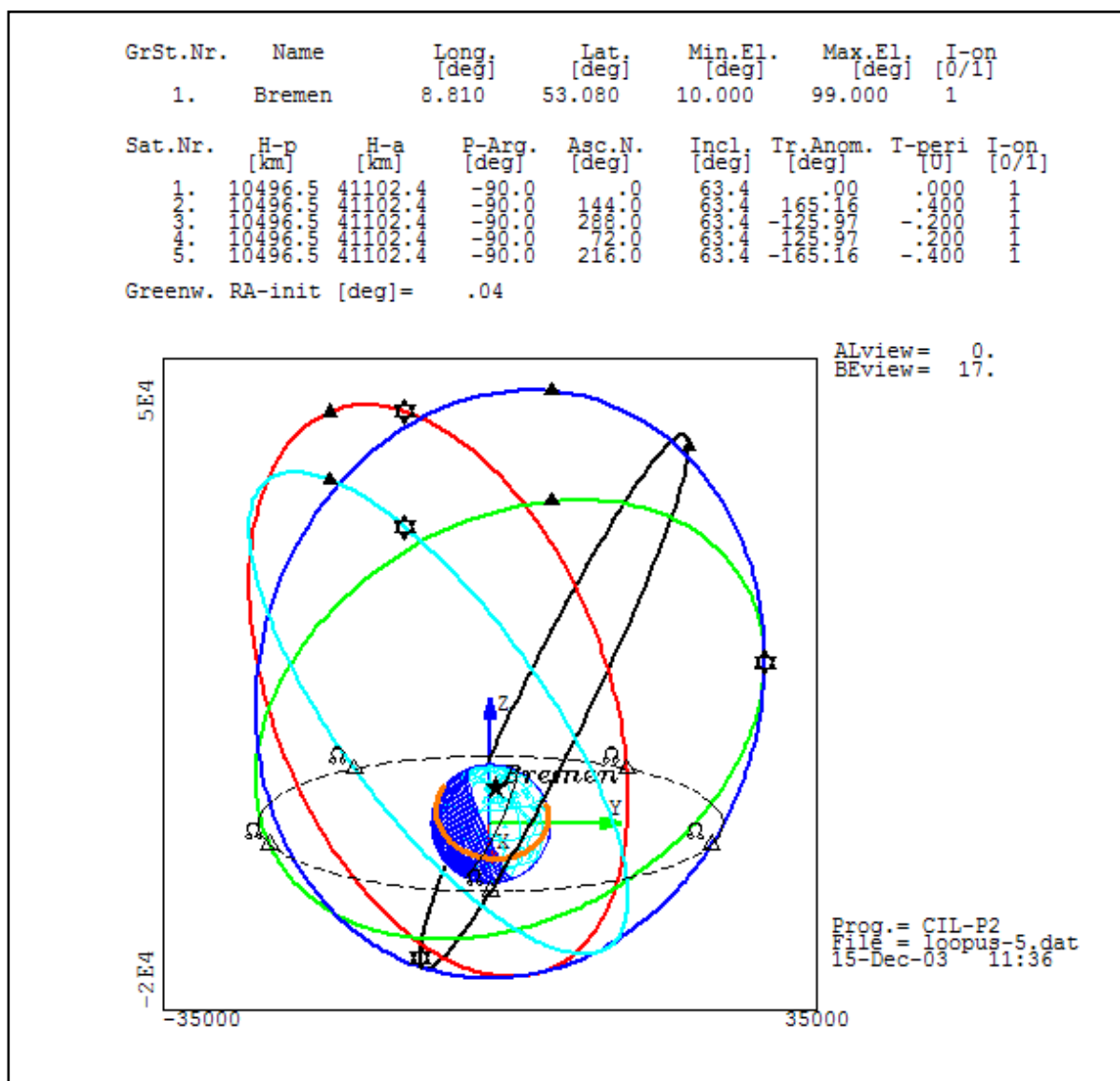
LOOPUS-Constellation with 3 Satellites

Contact Times to a Ground Station in Bremen

As the Loops are occupied by a Satellite continuously a quasi-stationary Contact is Provided

## 5 Satellites, 3 Loops

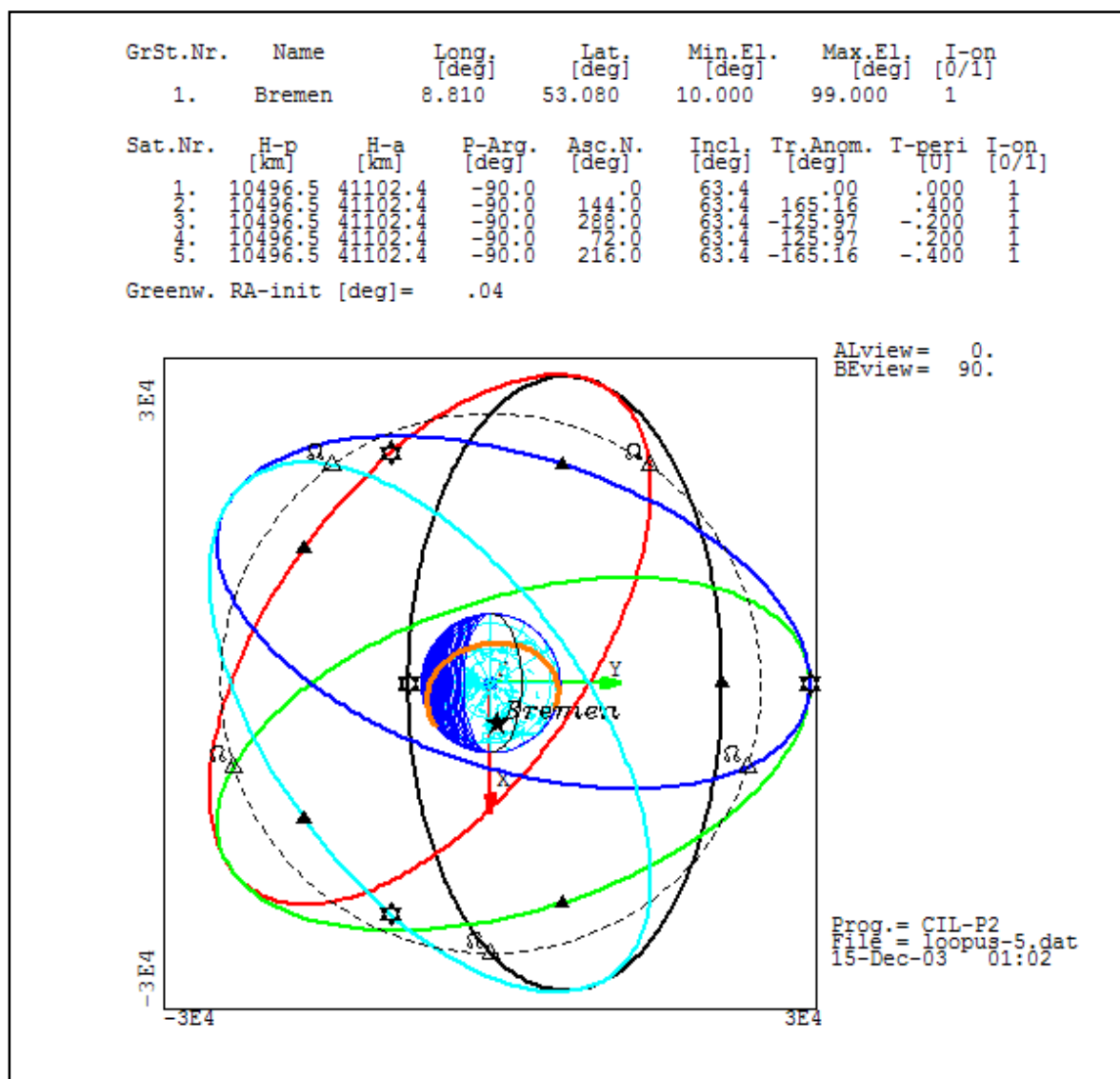
### 1.7 Inertial View, Perspective 1



LOOPUS-Constellation with 5 Satellites

Inertial View (geocentric, equatorial),  
Perspective 'flat' on Equator Plane

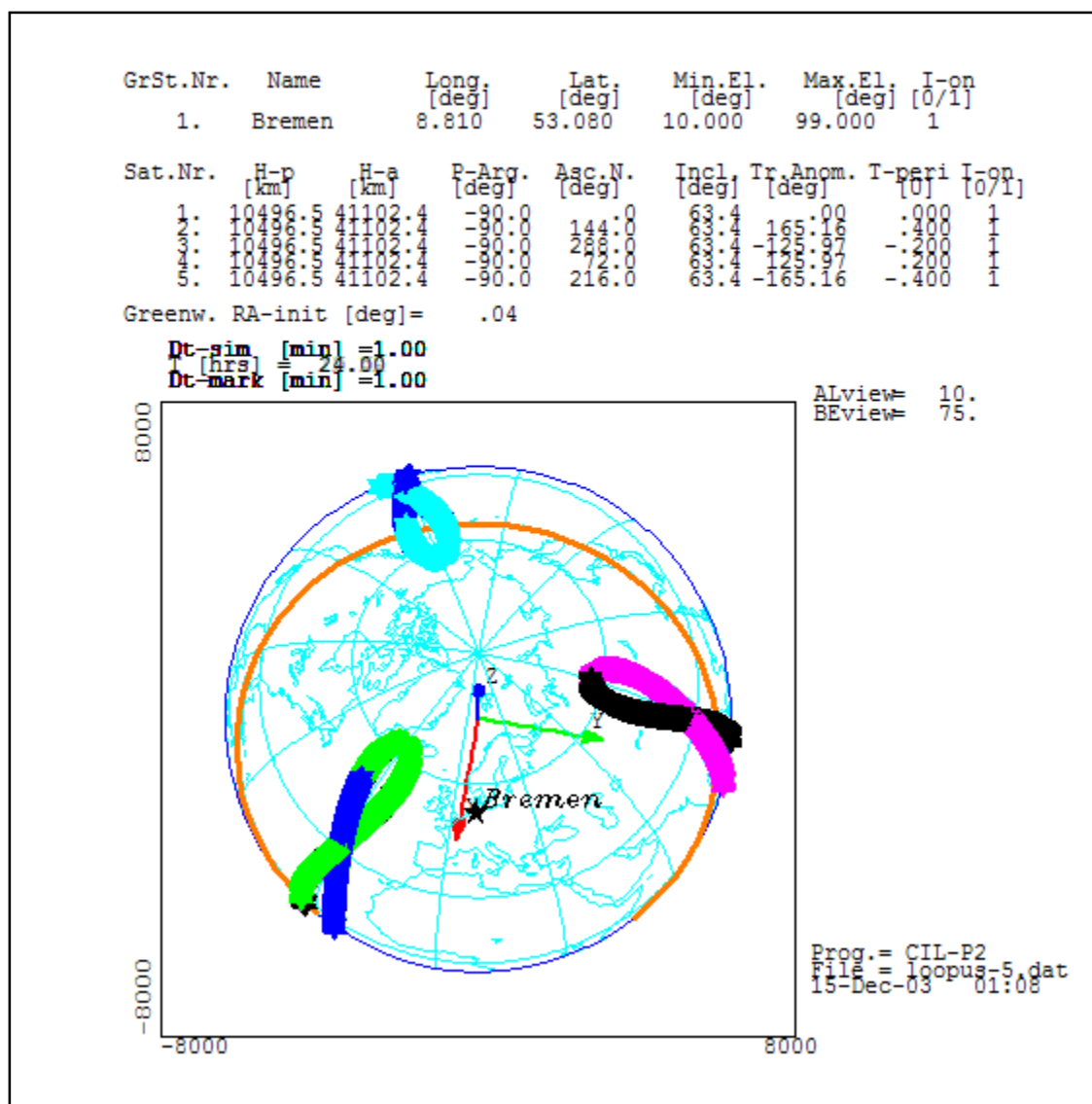
## 1.8 Inertial View, Perspective 2



LOOPUS-Constellation with 5 Satellites

Inertial View (geocentric, equatorial),  
Perspective 'top', on Northpole

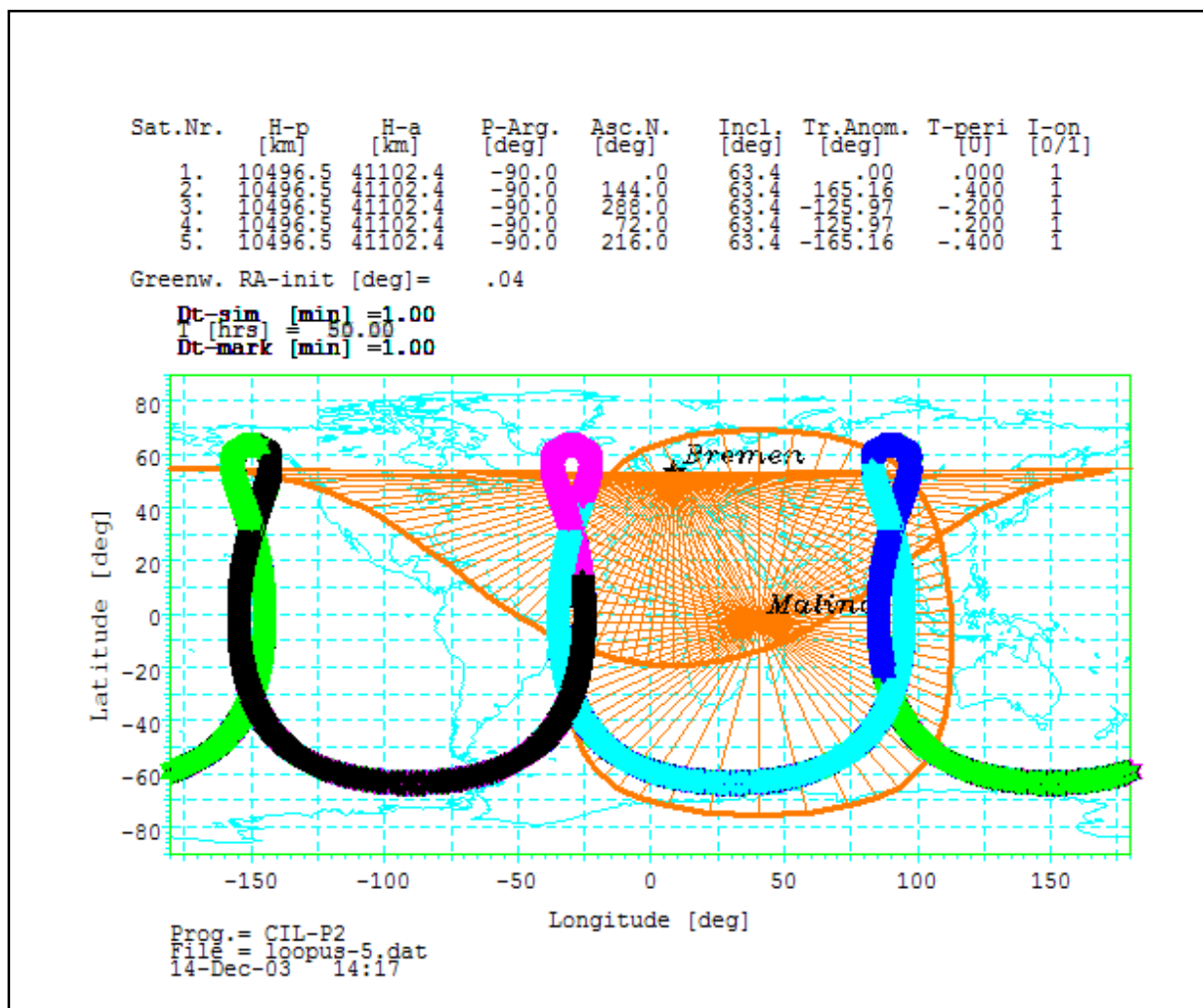
## 1.9 Groundtrack in Spherical Projection



LOOPUS-Constellation with 5 Satellites

generates 3 geostationary Groundtrack-Loops on the Northern Hemisphere

## 1.10 Groundtrack in Rectangular Projection



### LOOPUS-Constellation with 5 Satellites

generates a Groundtrack with 3 geostationary Loops  
on the Northern Hemisphere

Diagram in Rectangular Projection

Remarks:

- The Groundtrack (Position of the Loops) can be adjusted liberately in East-West-Direction at the beginning by a respective holding time on a LEO Parking Orbit ('Phasing'), but remains unchanged afterwards in the operational mode
- At the Cross-point of the Loops a change of the satellite occurs (one 'rises', the other 'sets').
- This results in a quasi-stationary Ground Contact Status



## 1.11 Loops of the Perspective from Bremen

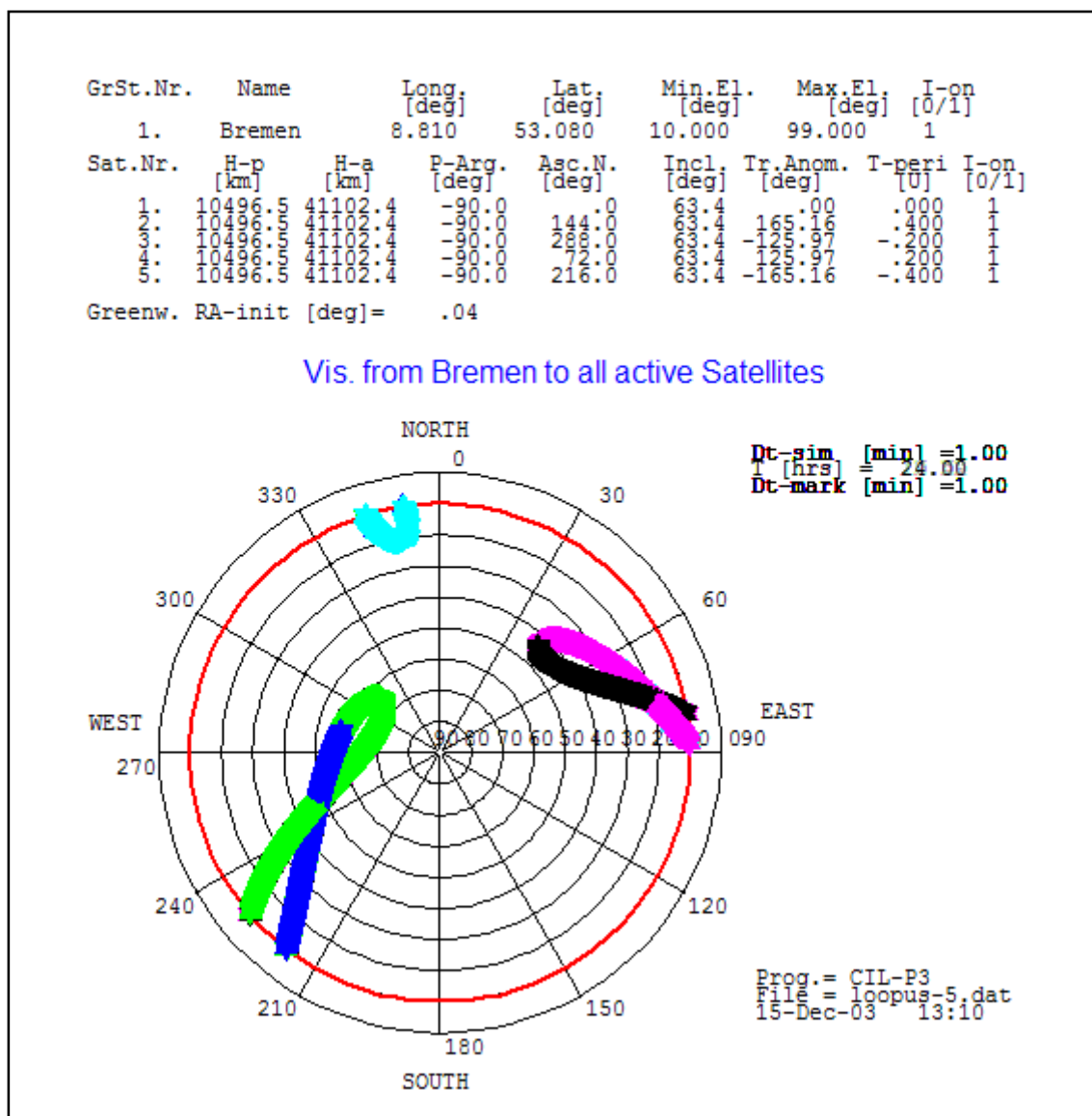
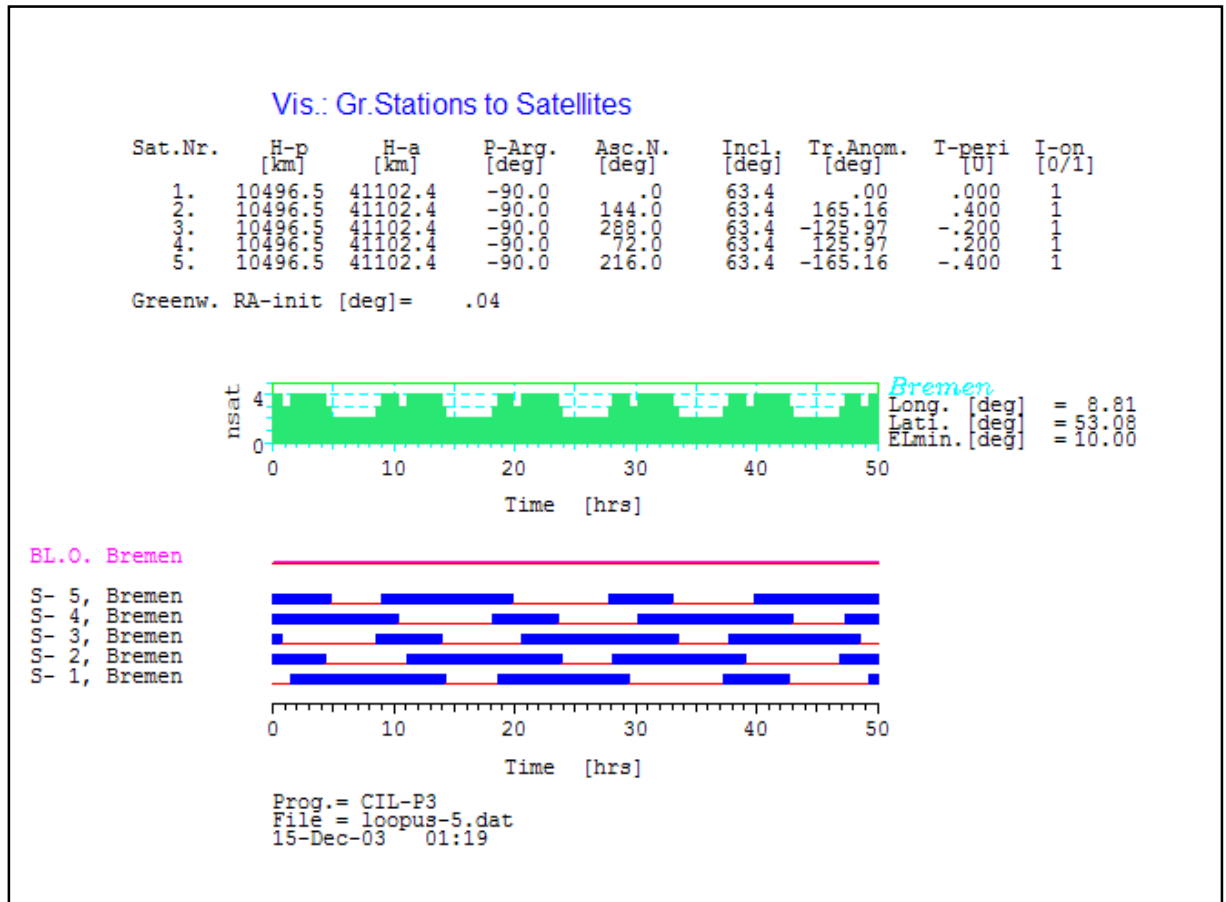


Diagram in Polar Coordinates of the Perspective from Bremen.

As the three Loops are occupied by a Satellite continuously a quasi-stationary Contact is Provided

## 1.12 Contact Timelines to Bremen



LOOPUS-Constellation with 5 Satellites

Contact Times to a Groundstation in Bremen.

As the three Loops are occupied by a Satellite continuously a quasi-stationary Contact is Provided

## C-2 Groundstation Contact Times

### 2 Orbits:

H = 700 / 700 km,  $i = 98,17^\circ$  (sun-sync.)

H = 1400 / 1400 km,  $i = 101,40^\circ$  (sun-sync.)

### 4 Groundstations:

Maspalomas

Madrid

Bremen

Kiruna

| GrSt.Nr. | Name       | Long.<br>[deg] | Lat.<br>[deg] | Min.El.<br>[deg] | Max.El.<br>[deg] | I-on<br>[0/1] |
|----------|------------|----------------|---------------|------------------|------------------|---------------|
| 1.       | Maspalomas | -15.632        | 27.763        | 10.000           | 99.000           | 1             |
| 2.       | Madrid     | -3.950         | 40.430        | 10.000           | 99.000           | 1             |
| 3.       | Bremen     | 8.810          | 53.080        | 10.000           | 99.000           | 1             |
| 4.       | Kiruna     | 21.070         | 67.880        | 10.000           | 99.000           | 1             |

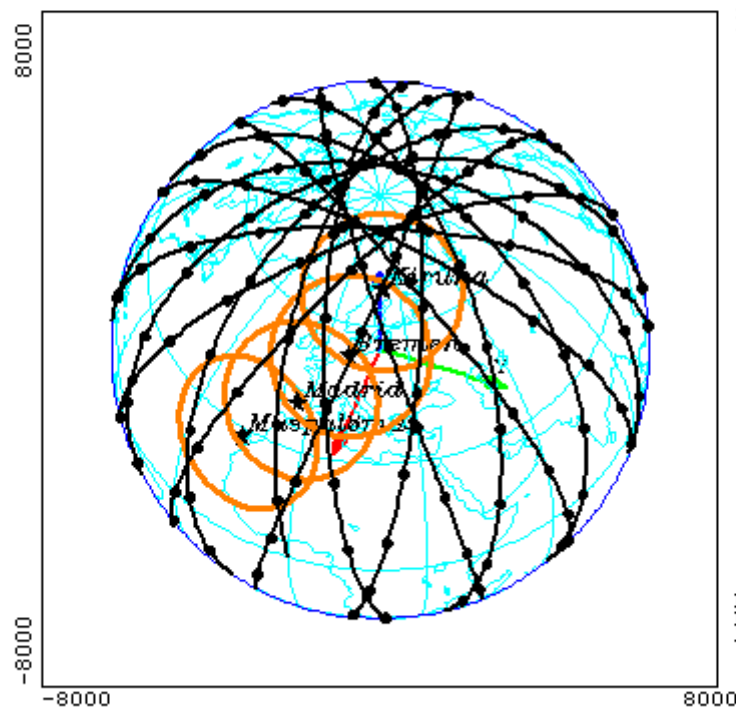
  

| Sat.Nr. | H-p<br>[km] | H-a<br>[km] | P-Arg.<br>[deg] | Asc.N.<br>[deg] | Incl.<br>[deg] | Tr.Anom.<br>[deg] | T-peri<br>[U] | I-on<br>[0/1] |
|---------|-------------|-------------|-----------------|-----------------|----------------|-------------------|---------------|---------------|
| 1.      | 700.0       | 700.0       | .0              | .0              | 98.2           | .00               | .000          | 1             |
| 2.      | 1400.0      | 1400.0      | .0              | .0              | 101.4          | .00               | .000          | 0             |

Greenw. RA-init [deg]= .04

T [hrs] = 24.00  
Dt-sim [min] = .5  
Dt-mark [min] = 5.0

ALview= 20.  
BEview= 55.



Prog. = CIL-P2  
File = ground-2.dat  
17-Dec-03 17:14

**Sat-1: H = 700 / 700 km, i = 98,2° (sun-sync.)**  
**Ground Track in Spherical Projection**

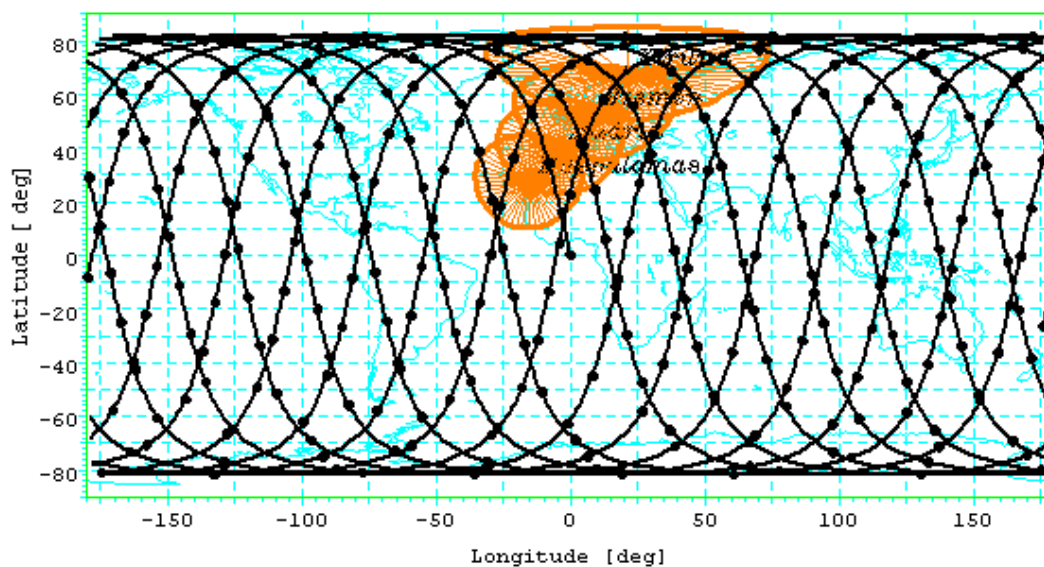
At quasi-polar Orbits Kiruna provides the best Contact Time Conditions

| GrSt.Nr. | Name       | Long.<br>[deg] | Lat.<br>[deg] | Min.El.<br>[deg] | Max.El.<br>[deg] | I-on<br>[0/1] |
|----------|------------|----------------|---------------|------------------|------------------|---------------|
| 1.       | Maspalomas | -15.632        | 27.763        | 10.000           | 99.000           | 1             |
| 2.       | Madrid     | -3.950         | 40.430        | 10.000           | 99.000           | 1             |
| 3.       | Bremen     | 8.810          | 53.080        | 10.000           | 99.000           | 1             |
| 4.       | Kiruna     | 21.070         | 67.880        | 10.000           | 99.000           | 1             |

| Sat.Nr. | H-p<br>[km] | H-a<br>[km] | P-Arg.<br>[deg] | Asc.N.<br>[deg] | Incl.<br>[deg] | Tr.Anom.<br>[deg] | T-peri<br>[U] | I-on<br>[0/1] |
|---------|-------------|-------------|-----------------|-----------------|----------------|-------------------|---------------|---------------|
| 1.      | 700.0       | 700.0       | .0              | .0              | 98.2           | .00               | .000          | 1             |
| 2.      | 1400.0      | 1400.0      | .0              | .0              | 101.4          | .00               | .000          | 0             |

Greenw. RA-init [deg]= .04  
 T [hrs] = 24.00  
 Dt-sim [min]= 5.5  
 Dt-mark [min]= 5.0



Prog.= CIL-P2  
 File = ground-2.dat  
 17-Dec-03 17:19

Sat-1: H = 700 / 700 km, i = 98,2° (sun-sync.)

**Ground Track in Rectangular Projection.** (Marker-Dist.= 5 min)

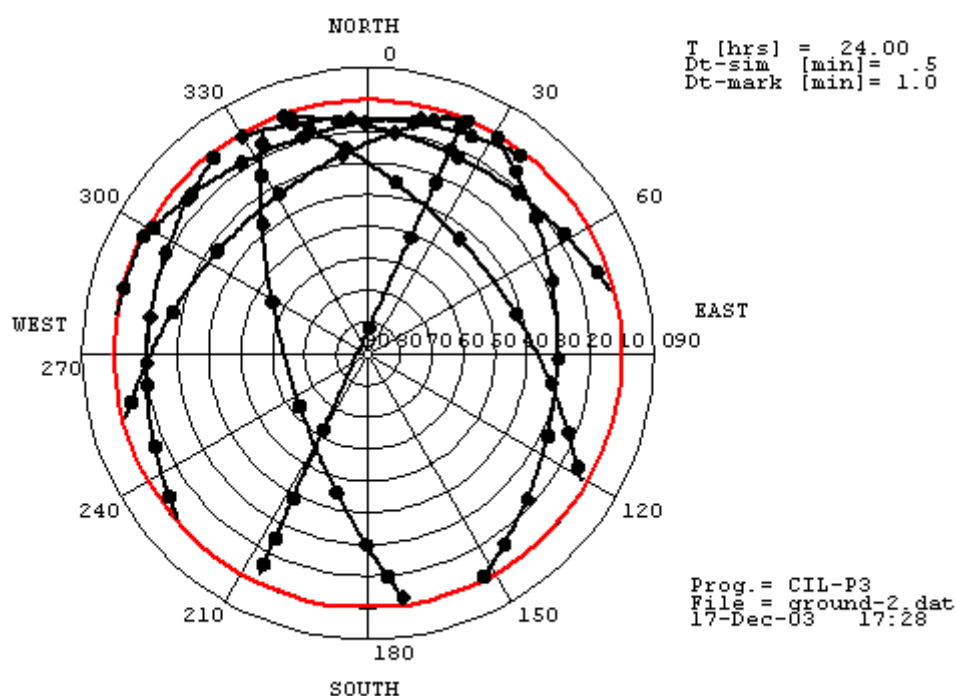
| GrSt.Nr. | Name       | Long.<br>[deg] | Lat.<br>[deg] | Min.El.<br>[deg] | Max.El.<br>[deg] | I-on<br>[0/1] |
|----------|------------|----------------|---------------|------------------|------------------|---------------|
| 1.       | Maspalomas | -15.632        | 27.763        | 10.000           | 99.000           | 1             |
| 2.       | Madrid     | -3.950         | 40.430        | 10.000           | 99.000           | 1             |
| 3.       | Bremen     | 8.810          | 53.080        | 10.000           | 99.000           | 1             |
| 4.       | Kiruna     | 21.070         | 67.880        | 10.000           | 99.000           | 1             |

| Sat.Nr. | H-p<br>[km] | H-a<br>[km] | P-Arg.<br>[deg] | Asc.N.<br>[deg] | Incl.<br>[deg] | Tr.Anom.<br>[deg] | T-peri<br>[0] | I-on<br>[0/1] |
|---------|-------------|-------------|-----------------|-----------------|----------------|-------------------|---------------|---------------|
| 1.      | 700.0       | 700.0       | .0              | .0              | 98.2           | .00               | .000          | 1             |
| 2.      | 1400.0      | 1400.0      | .0              | .0              | 101.4          | .00               | .000          | 0             |

Greenw. RA-init [deg]= .04

Vis. from Kiruna to Sat-1



Sat-1: H = 700 / 700 km, i = 98,2° (sun-sync.)  
From Kiruna Perspective

Marker-Distance = 1 min.

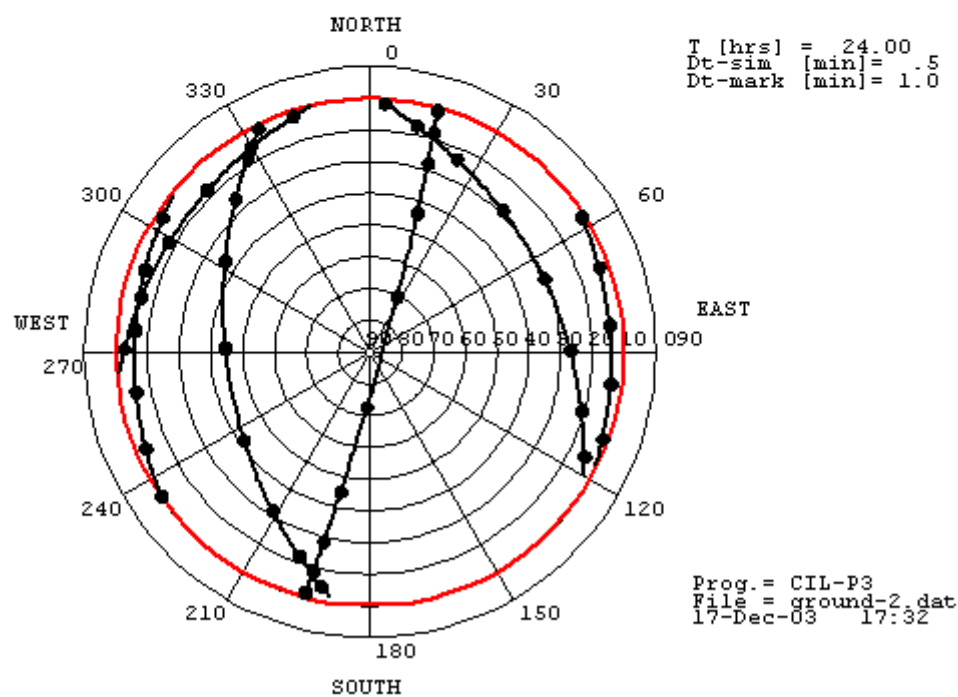
| GrSt.Nr. | Name       | Long.<br>[deg] | Lat.<br>[deg] | Min.El.<br>[deg] | Max.El.<br>[deg] | I-on<br>[0/1] |
|----------|------------|----------------|---------------|------------------|------------------|---------------|
| 1.       | Maspalomas | -15.632        | 27.763        | 10.000           | 99.000           | 1             |
| 2.       | Madrid     | -3.950         | 40.430        | 10.000           | 99.000           | 1             |
| 3.       | Bremen     | 8.810          | 53.080        | 10.000           | 99.000           | 1             |
| 4.       | Kiruna     | 21.070         | 67.880        | 10.000           | 99.000           | 1             |

| Sat.Nr. | H-p<br>[km] | H-a<br>[km] | P-Arg.<br>[deg] | Asc.N.<br>[deg] | Incl.<br>[deg] | Tr.Anom.<br>[deg] | T-peri<br>[U] | I-on<br>[0/1] |
|---------|-------------|-------------|-----------------|-----------------|----------------|-------------------|---------------|---------------|
| 1.      | 700.0       | 700.0       | .0              | .0              | 98.2           | .00               | .000          | 1             |
| 2.      | 1400.0      | 1400.0      | .0              | .0              | 101.4          | .00               | .000          | 0             |

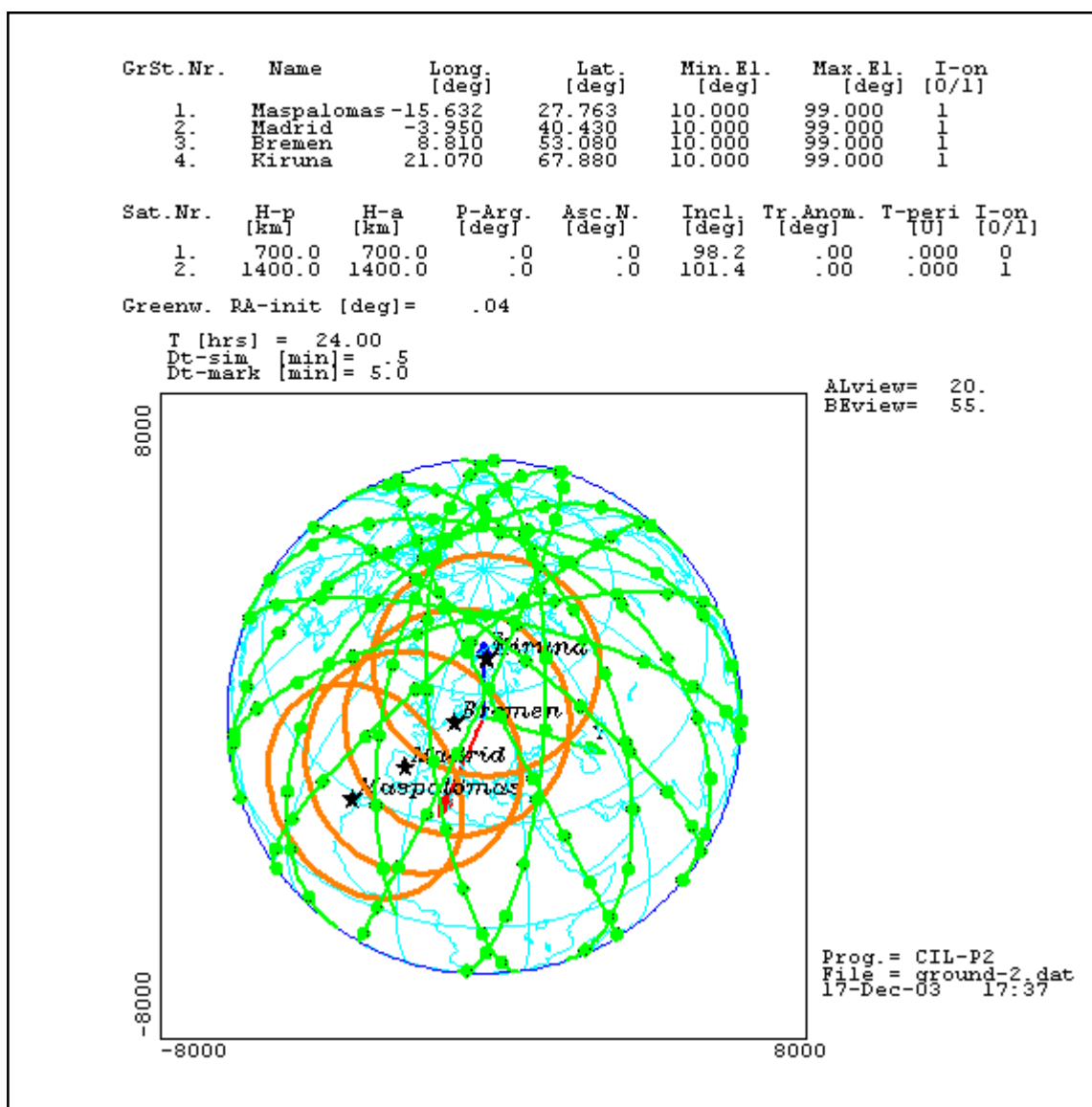
Greenw. RA-init [deg]= .04

Vis. from Bremen to Sat-1



**Sat-1: H = 700 / 700 km, i = 98,2° (sun-sync.)**  
**From Bremen Perspective**

Marker-Distance = 1 min.



**Sat-2: H = 1400 / 1400 km, i = 101,4° (sun-sync.)**

**Ground Track in Spherical Projection**

Marker-Distance = 5 min.

The Contact Reach Area of Kiruna exceeds already over the Northpole

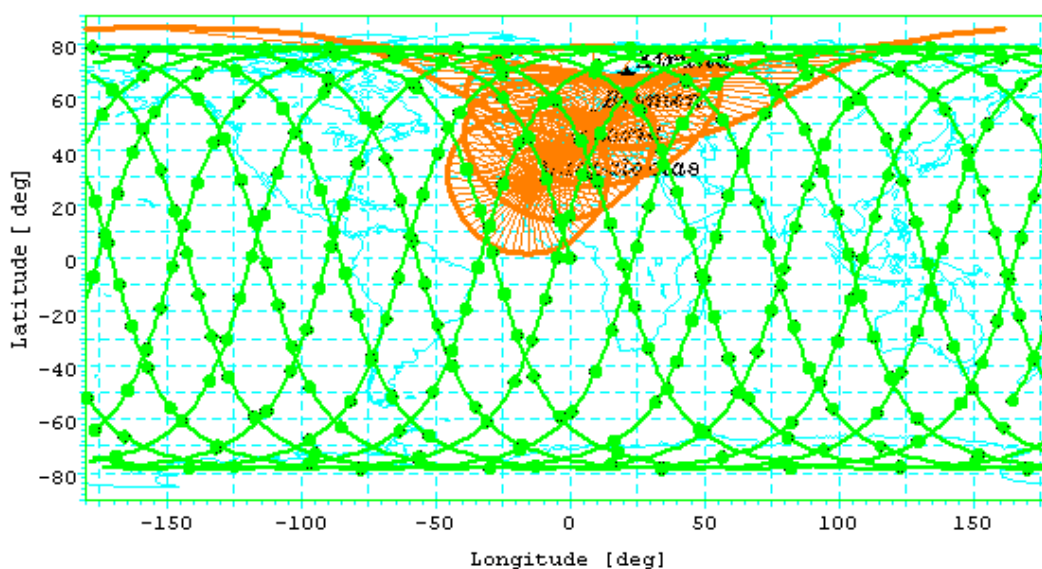


| GrSt.Nr. | Name       | Long.<br>[deg] | Lat.<br>[deg] | Min.El.<br>[deg] | Max.El.<br>[deg] | I-on<br>[0/1] |
|----------|------------|----------------|---------------|------------------|------------------|---------------|
| 1.       | Maspalomas | -15.632        | 27.763        | 10.000           | 99.000           | 1             |
| 2.       | Madrid     | -3.950         | 40.430        | 10.000           | 99.000           | 1             |
| 3.       | Bremen     | 8.810          | 53.080        | 10.000           | 99.000           | 1             |
| 4.       | Kiruna     | 21.070         | 67.880        | 10.000           | 99.000           | 1             |

| Sat.Nr. | H-p<br>[km] | H-a<br>[km] | P-Arg.<br>[deg] | Asc.N.<br>[deg] | Incl.<br>[deg] | Tr.Anom.<br>[deg] | T-peri<br>[U] | I-on<br>[0/1] |
|---------|-------------|-------------|-----------------|-----------------|----------------|-------------------|---------------|---------------|
| 1.      | 700.0       | 700.0       | .0              | .0              | 98.2           | .00               | .000          | 0             |
| 2.      | 1400.0      | 1400.0      | .0              | .0              | 101.4          | .00               | .000          | 1             |

Greenw. RA-init [deg]= .04  
T [hrs] = 24.00  
Dt-sim [min]= 5.5  
Dt-mark [min]= 5.0



Prog. = CIL-P2  
File = ground-2.dat  
17-Dec-03 17:40

**Sat-2: H = 1400 / 1400 km, i = 101,4° (sun-sync.)**

**Ground Track in Rectangular Projection**

Marker Distance = 5 min.

The Contact Reach Area of Kiruna exceeds already over the Northpole

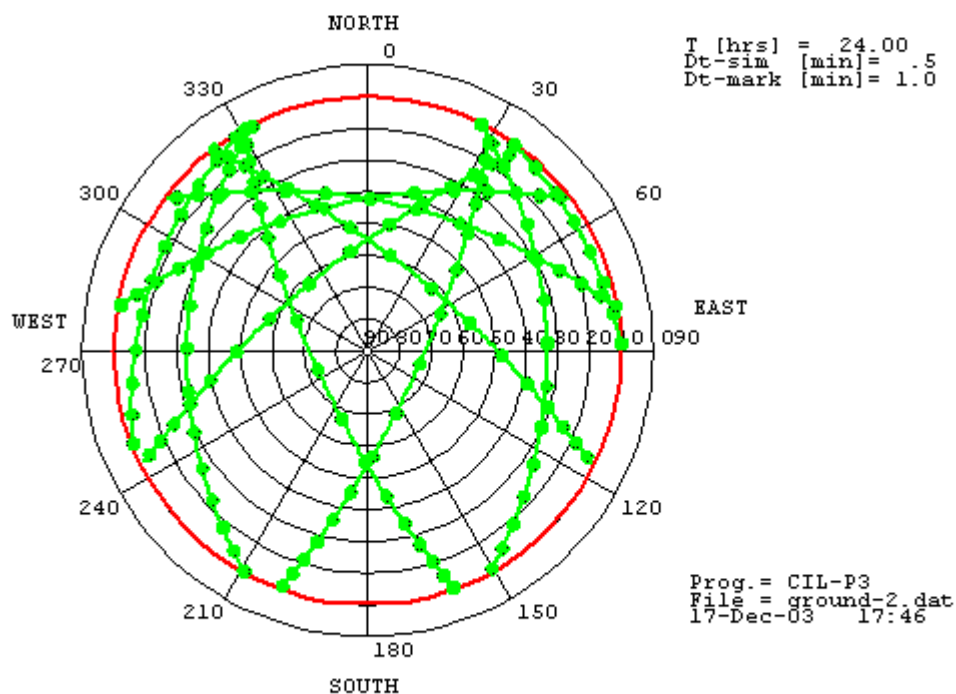
| GrSt.Nr. | Name       | Long.<br>[deg] | Lat.<br>[deg] | Min.El.<br>[deg] | Max.El.<br>[deg] | I-on<br>[0/1] |
|----------|------------|----------------|---------------|------------------|------------------|---------------|
| 1.       | Maspalomas | -15.632        | 27.763        | 10.000           | 99.000           | 1             |
| 2.       | Madrid     | -3.950         | 40.430        | 10.000           | 99.000           | 1             |
| 3.       | Bremen     | 8.810          | 53.080        | 10.000           | 99.000           | 1             |
| 4.       | Kiruna     | 21.070         | 67.880        | 10.000           | 99.000           | 1             |

| Sat.Nr. | H-p<br>[km] | H-a<br>[km] | P-Arg.<br>[deg] | Asc.N.<br>[deg] | Incl.<br>[deg] | Tr.Anom.<br>[deg] | T-peri<br>[0] | I-on<br>[0/1] |
|---------|-------------|-------------|-----------------|-----------------|----------------|-------------------|---------------|---------------|
| 1.      | 700.0       | 700.0       | .0              | .0              | 98.2           | .00               | .000          | 0             |
| 2.      | 1400.0      | 1400.0      | .0              | .0              | 101.4          | .00               | .000          | 1             |

Greenw. RA-init [deg]= .04

Vis. from Kiruna to Sat-2



**Sat-2: H = 1400 / 1400 km, i = 101,4° (sun-sync.)**  
**Aus der Sicht von Kiruna**

Marker Distance = 1 min.

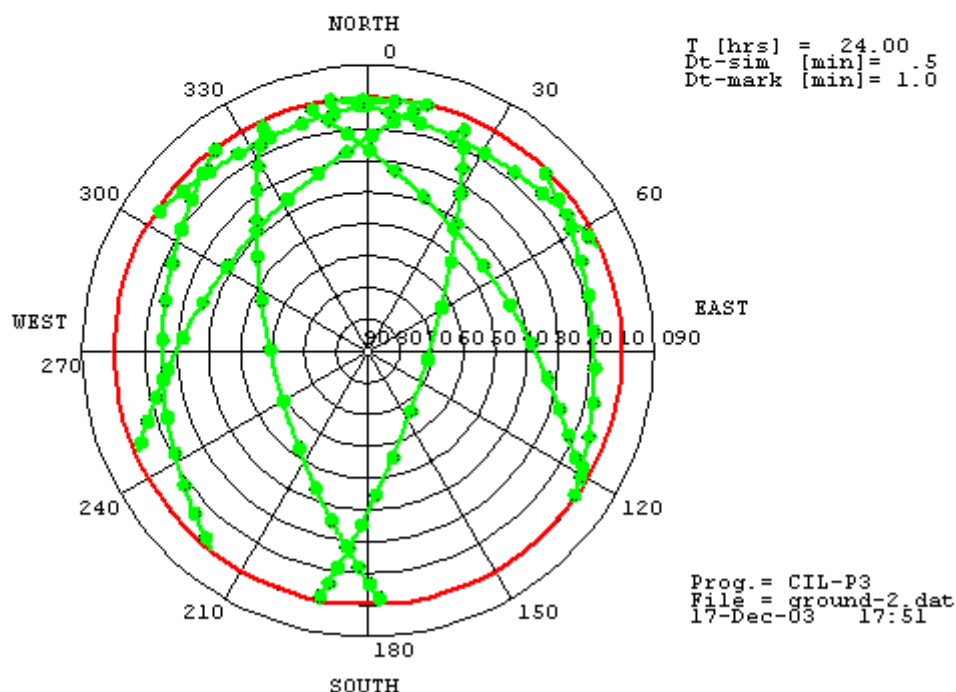
| GrSt.Nr. | Name       | Long.<br>[deg] | Lat.<br>[deg] | Min.El.<br>[deg] | Max.El.<br>[deg] | I-on<br>[0/1] |
|----------|------------|----------------|---------------|------------------|------------------|---------------|
| 1.       | Maspalomas | -15.632        | 27.763        | 10.000           | 99.000           | 1             |
| 2.       | Madrid     | -3.950         | 40.430        | 10.000           | 99.000           | 1             |
| 3.       | Bremen     | 8.810          | 53.080        | 10.000           | 99.000           | 1             |
| 4.       | Kiruna     | 21.070         | 67.880        | 10.000           | 99.000           | 1             |

| Sat.Nr. | H-p<br>[km] | H-a<br>[km] | P-Arg.<br>[deg] | Asc.N.<br>[deg] | Incl.<br>[deg] | Tr.Anom.<br>[deg] | T-peri<br>[0] | I-on<br>[0/1] |
|---------|-------------|-------------|-----------------|-----------------|----------------|-------------------|---------------|---------------|
| 1.      | 700.0       | 700.0       | .0              | .0              | 98.2           | .00               | .000          | 0             |
| 2.      | 1400.0      | 1400.0      | .0              | .0              | 101.4          | .00               | .000          | 1             |

Greenw. RA-init [deg]= .04

Vis. from Bremen to Sat-2



**Sat-2: H = 1400 / 1400 km, i = 101,4° (sun-sync.)**  
**Aus der Sicht von Bremen**

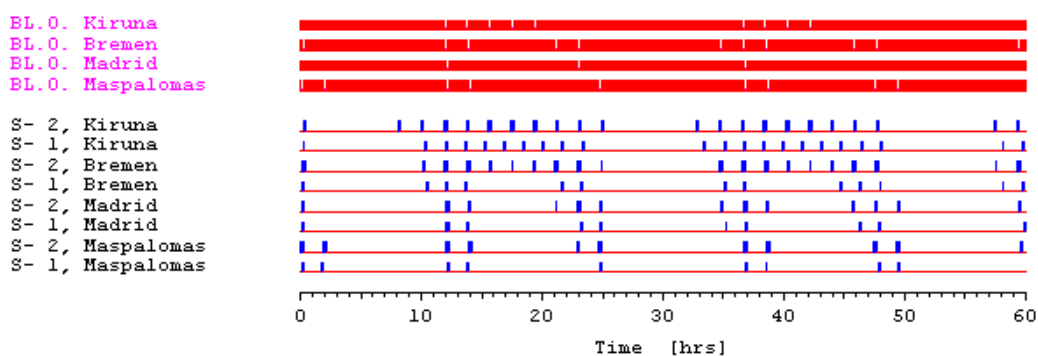
Marker-Abstand = 1 min.

| GrSt.Nr. | Name       | Long.<br>[deg] | Lat.<br>[deg] | Min.El.<br>[deg] | Max.El.<br>[deg] | I-on<br>[0/1] |
|----------|------------|----------------|---------------|------------------|------------------|---------------|
| 1.       | Maspalomas | -15.632        | 27.763        | 10.000           | 99.000           | 1             |
| 2.       | Madrid     | -3.950         | 40.430        | 10.000           | 99.000           | 1             |
| 3.       | Bremen     | 8.810          | 53.080        | 10.000           | 99.000           | 1             |
| 4.       | Kiruna     | 21.070         | 67.880        | 10.000           | 99.000           | 1             |

Vis.: Gr.Stations to Satellites

| Sat.Nr. | H-p<br>[km] | H-a<br>[km] | P-Arg.<br>[deg] | Asc.N.<br>[deg] | Incl.<br>[deg] | Tr.Anom.<br>[deg] | T-peri<br>[U] | I-on<br>[0/1] |
|---------|-------------|-------------|-----------------|-----------------|----------------|-------------------|---------------|---------------|
| 1.      | 700.0       | 700.0       | .0              | .0              | 98.2           | .00               | .000          | 1             |
| 2.      | 1400.0      | 1400.0      | .0              | .0              | 101.4          | .00               | .000          | 1             |

Greenw. RA-init [deg]= .04



Prog.= CIL-P3  
File = ground-2.dat  
17-Dec-03 17:54

## Contact-Pattern for the 2 Orbits with the 4 Ground Stations

Simulation time = 60 hrs.

|                |   |                                             |
|----------------|---|---------------------------------------------|
| $EL_{min}$     | = | Rim-Elevation at local horizon              |
| $T_{sum}$      | = | total Contact time in 10 days               |
| $T_{sum} / 10$ | = | average Contact time in 1 day               |
| $N$            | = | Number Contacts in 10 Days                  |
| $T_{aver}$     | = | $T_{sum} / N$ = average Single-Contact time |

## CASE 1

-----  
**Orbit: H = 700/700 km, i = 98,2° (sun-sync.)**  
 -----

**TOTAL FLIGHT TIME = 14400.00 min = 240.00 hrs = 10.00 days**

GROUND CONTACT PERCENTAGES:

| NAME    | LONG.<br>[deg] | LAT.<br>[deg] | EL_min<br>[deg] | Tsum<br>[min] | N<br>[-] | Taver<br>[min] | Tproz<br>[%] |
|---------|----------------|---------------|-----------------|---------------|----------|----------------|--------------|
| Maspal. | -15.60         | 26.50         | 10.00           | 247.17        | 34       | 7.27           | 1.72         |
| Madrid  | -3.95          | 40.43         | 10.00           | 289.99        | 39       | 7.44           | 2.01         |
| Bremen  | 8.81           | 53.08         | 10.00           | 380.38        | 52       | 7.31           | 2.64         |
| Kiruna  | 21.07          | 67.88         | 10.00           | 727.76        | 96       | 7.58           | 5.05         |

## CASE 2

-----  
**Orbit: H = 1400/1400 km, i = 101,4° (sun-sync.)**  
 -----

**TOTAL FLIGHT TIME = 14400.00 min = 240.00 hrs = 10.00 days**

GROUND CONTACT PERCENTAGES:

| NAME    | LONG.<br>[deg] | LAT.<br>[deg] | EL_min<br>[deg] | Tsum<br>[min] | N<br>[-] | Taver<br>[min] | Tproz<br>[%] |
|---------|----------------|---------------|-----------------|---------------|----------|----------------|--------------|
| Maspal. | -15.60         | 26.50         | 10.00           | 567.63        | 44       | 12.90          | 3.94         |
| Madrid  | -3.95          | 40.43         | 10.00           | 685.95        | 54       | 12.70          | 4.76         |
| Bremen  | 8.81           | 53.08         | 10.00           | 1007.55       | 86       | 11.72          | 7.00         |
| Kiruna  | 21.07          | 67.88         | 10.00           | 1352.52       | 96       | 14.09          | 9.39         |

## C-3 Groundstations-Contact Times

### 2 Orbits:

H = 400 / 400 km,  $i = 51.6^\circ$

H = 1000 / 1000 km,  $i = 51.6^\circ$

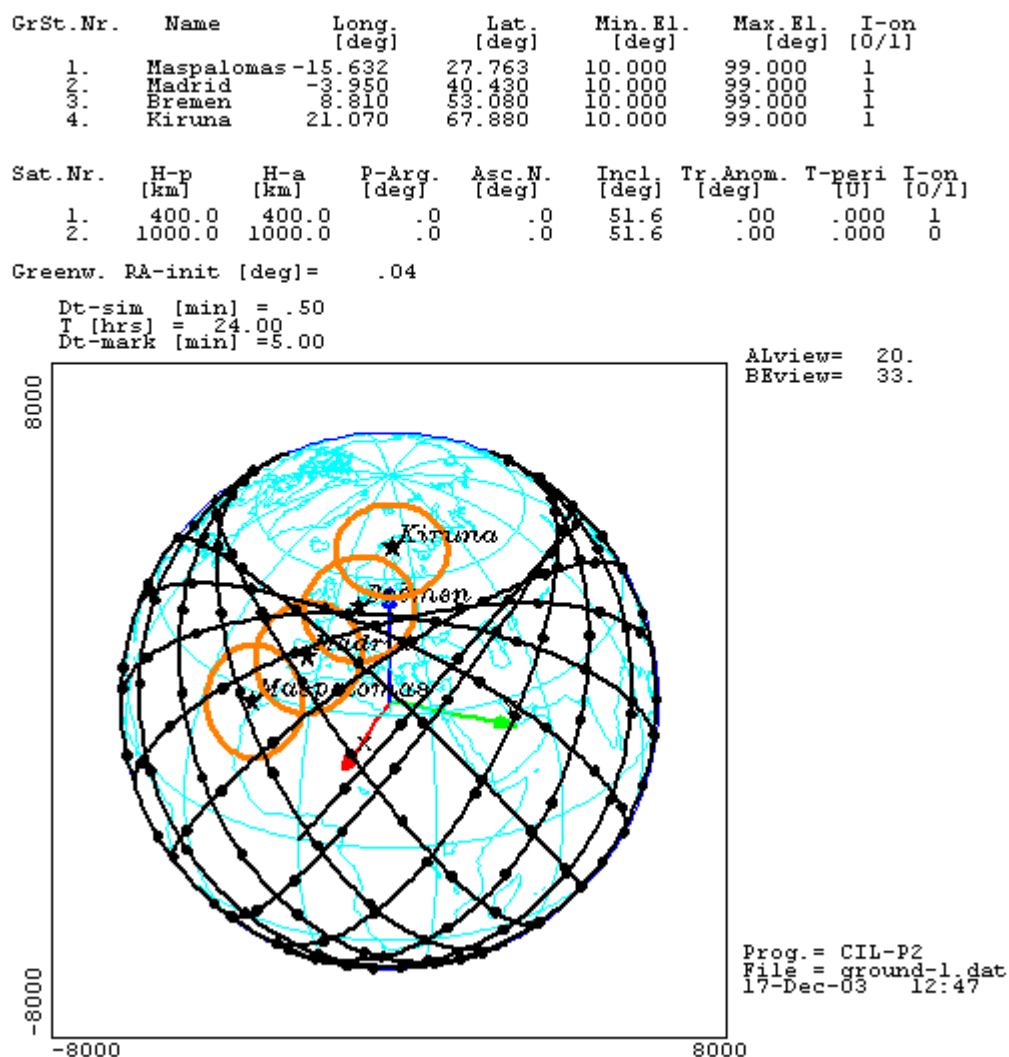
### 4 Groundstations:

Maspalomas

Madrid

Bremen

Kiruna



**Sat-1: H = 400 / 400 km, i=51.6°**  
**Ground Track in Spherical Projection**

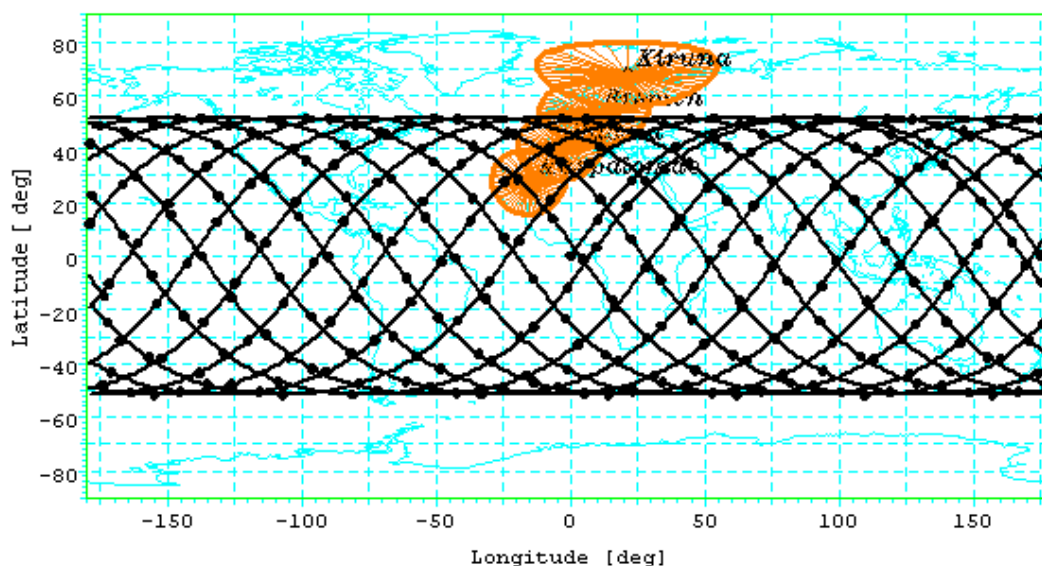
**At this Orbital Height and Inclination Kiruna has no Contact Time**

| GrSt.Nr. | Name       | Long.<br>[deg] | Lat.<br>[deg] | Min.El.<br>[deg] | Max.El.<br>[deg] | I-on<br>[0/1] |
|----------|------------|----------------|---------------|------------------|------------------|---------------|
| 1.       | Maspalomas | -15.632        | 27.763        | 10.000           | 99.000           | 1             |
| 2.       | Madrid     | -3.950         | 40.430        | 10.000           | 99.000           | 1             |
| 3.       | Bremen     | 8.810          | 53.080        | 10.000           | 99.000           | 1             |
| 4.       | Kiruna     | 21.070         | 67.880        | 10.000           | 99.000           | 1             |

| Sat.Nr. | H-p<br>[km] | H-a<br>[km] | P-Arg.<br>[deg] | Asc.N.<br>[deg] | Incl.<br>[deg] | Tr.Anom.<br>[deg] | T-peri<br>[U] | I-on<br>[0/1] |
|---------|-------------|-------------|-----------------|-----------------|----------------|-------------------|---------------|---------------|
| 1.      | 400.0       | 400.0       | .0              | .0              | 51.6           | .00               | .000          | 1             |
| 2.      | 1000.0      | 1000.0      | .0              | .0              | 51.6           | .00               | .000          | 0             |

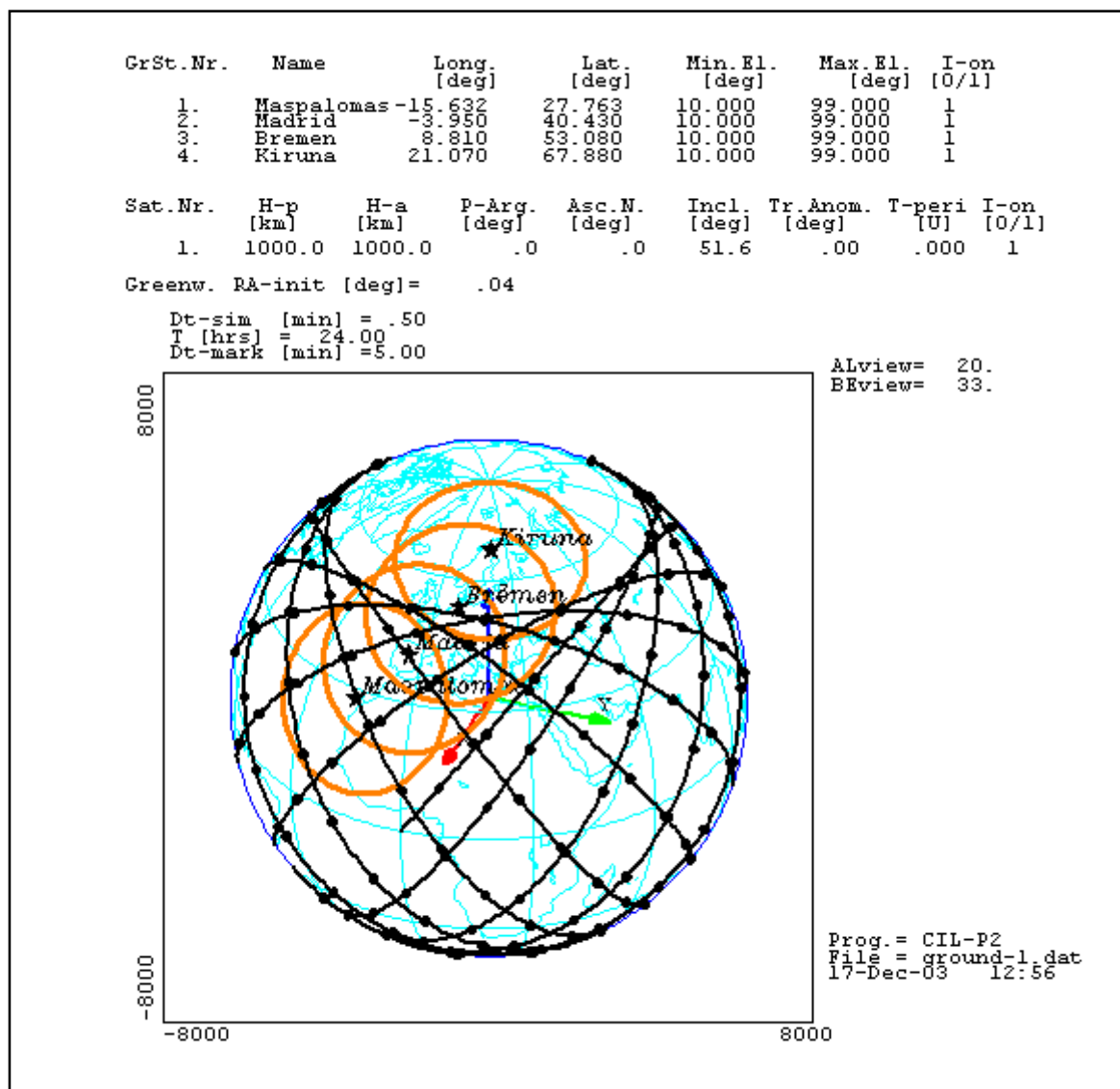
Greenw. RA-init [deg]= .04  
Dt-sim [min] = .50  
T [hrs] = 24.00  
Dt-mark [min] = 5.00



Prog. = CIL-P2  
File = ground-1.dat  
17-Dec-03 12:43

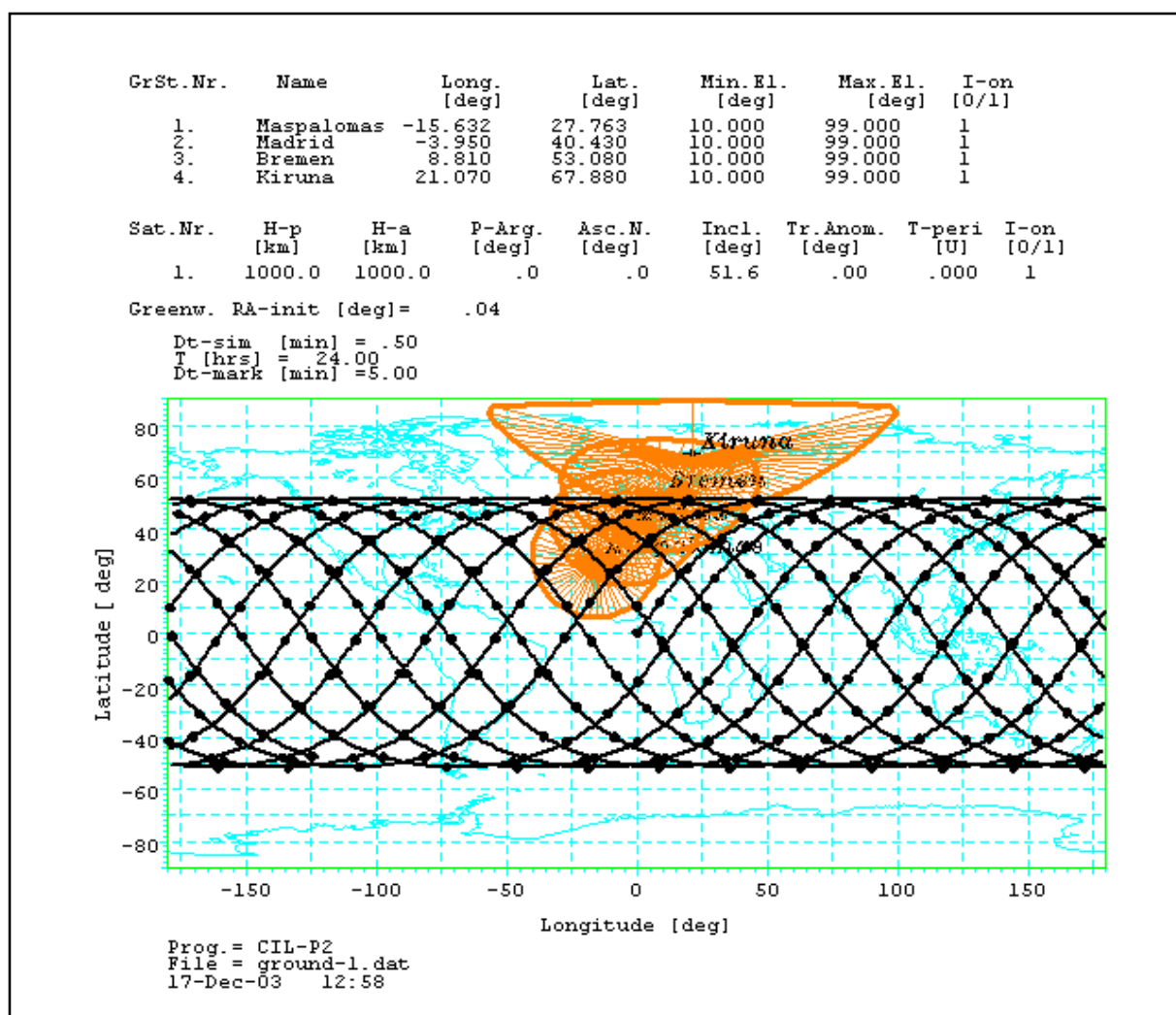
**Sat-1: H = 400 / 400 km, i = 51.6°**  
**Ground Track in Rectangular Projection (Marker-Dist.= 5 min)**





**Sat-2:  $H = 1000 / 1000$  km,  $i = 51.6^\circ$**   
**Ground Track in Spherical Projection**

At this Orbital Hight Kiruna starts to have a Short Contact Time



**Sat-2: 1000 / 1000 km,  $i = 51.6^\circ$  . .**

**Ground Track in Rectangular Projection. (Marker-Dist.= 5 min)**

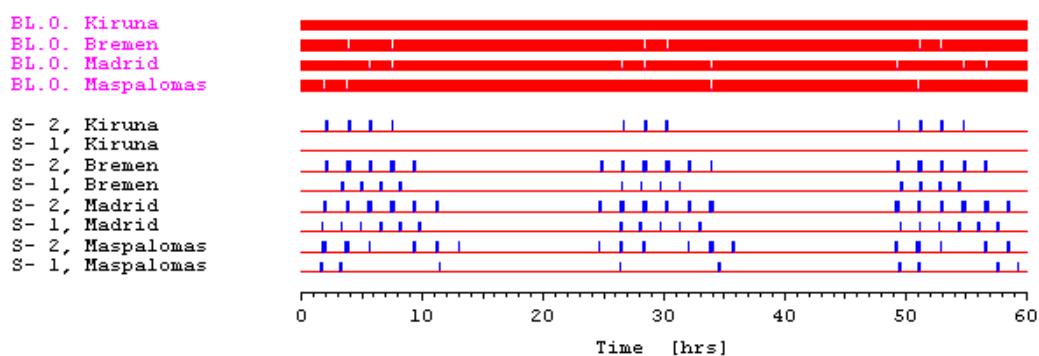
The Contact Reach Areas are increased here due to the higher Orbit

| GrSt.Nr. | Name       | Long.<br>[deg] | Lat.<br>[deg] | Min.El.<br>[deg] | Max.El.<br>[deg] | I-on<br>[0/1] |
|----------|------------|----------------|---------------|------------------|------------------|---------------|
| 1.       | Maspalomas | -15.632        | 27.763        | 10.000           | 99.000           | 1             |
| 2.       | Madrid     | -3.950         | 40.430        | 10.000           | 99.000           | 1             |
| 3.       | Bremen     | 8.810          | 53.080        | 10.000           | 99.000           | 1             |
| 4.       | Kiruna     | 21.070         | 67.880        | 10.000           | 99.000           | 1             |

## Vis.: Gr.Stations to Satellites

| Sat.Nr. | H-p<br>[km] | H-a<br>[km] | P-Arg.<br>[deg] | Asc.N.<br>[deg] | Incl.<br>[deg] | Tr.Anom.<br>[deg] | T-peri<br>[U] | I-on<br>[0/1] |
|---------|-------------|-------------|-----------------|-----------------|----------------|-------------------|---------------|---------------|
| 1.      | 400.0       | 400.0       | .0              | .0              | 51.6           | .00               | .000          | 1             |
| 2.      | 1000.0      | 1000.0      | .0              | .0              | 51.6           | .00               | .000          | 1             |

Greenw. RA-init [deg]= .04



Prog.= CIL-P3  
File = ground-1.dat  
17-Dec-03 13:06

**Contact-Pattern for the 2 Orbits with the 4 Ground Stations**  
**Simulation time = 60 hrs.**

|                |   |                                             |
|----------------|---|---------------------------------------------|
| $EL_{min}$     | = | Rim-Elevation at local Horizont             |
| $T_{sum}$      | = | Total Contact time in 10 Days               |
| $T_{sum} / 10$ | = | average Contact time in 1 day               |
| $N$            | = | Number Contacts in 10 days                  |
| $T_{aver}$     | = | $T_{sum} / N$ = average Single Contact time |

## CASE 1

-----  
**Orbit: H = 400/400 km, i = 51.6 deg**  
 -----

**TOTAL FLIGHT TIME = 14400.000 min = 240.000 hrs = 10.000 days**

GROUND CONTACT PERCENTAGES:

| NAME    | LONG.<br>[deg] | LAT.<br>[deg] | EL_min<br>[deg] | Tsum<br>[min] | N<br>[-] | Taver<br>[min] | Tproz<br>[%] |
|---------|----------------|---------------|-----------------|---------------|----------|----------------|--------------|
| -----   | -----          | -----         | -----           | -----         | -----    | -----          | -----        |
| -       |                |               |                 |               |          |                |              |
| Maspal. | -15.60         | 26.50         | 10.00           | 160.03        | 33       | 4.85           | 1.11         |
| Madrid  | -3.95          | 40.43         | 10.00           | 277.81        | 57       | 4.87           | 1.93         |
| Bremen  | 8.81           | 53.08         | 10.00           | 239.72        | 45       | 5.33           | 1.66         |
| Kiruna  | 21.07          | 67.88         | 10.00           | 0.00          | 0        | 0.00           | 0.00         |
| -----   | -----          | -----         | -----           | -----         | -----    | -----          | -----        |

## CASE 2

-----  
**Orbit: H = 1000/1000 km, i = 51.6 deg**  
 -----

**TOTAL FLIGHT TIME = 14400.000 min = 240.000 hrs = 10.000 days**

GROUND CONTACT PERCENTAGES:

| NAME    | LONG.<br>[deg] | LAT.<br>[deg] | EL_min<br>[deg] | Tsum<br>[min] | N<br>[-] | Taver<br>[min] | Tproz<br>[%] |
|---------|----------------|---------------|-----------------|---------------|----------|----------------|--------------|
| -----   | -----          | -----         | -----           | -----         | -----    | -----          | -----        |
| Maspal. | -15.60         | 26.50         | 10.00           | 541.91        | 55       | 9.85           | 3.76         |
| Madrid  | -3.95          | 40.43         | 10.00           | 732.26        | 63       | 11.62          | 5.09         |
| Bremen  | 8.81           | 53.08         | 10.00           | 608.55        | 53       | 11.48          | 4.23         |
| Kiruna  | 21.07          | 67.88         | 10.00           | 234.35        | 34       | 6.89           | 1.63         |
| -----   | -----          | -----         | -----           | -----         | -----    | -----          | -----        |

## 8.2 Detailed Calculation Results of the Terrestrial Power Supply

The results of the terrestrial part will be listed here in the appendix in more detail.

### 8.2.1 Base Load Demand Today

The data for base load demand are presented for the different power levels from 500 MW to 150 GW for respectively Photovoltaic (A) or Solar Thermal Power Plants (B).

#### 8.2.1.1 500 MW Base Load Today

Generation zone is zone A1 connected to Spain (E). As there yet exists the transmission line T1, no new line has to be built. The difference between the “Reference Transmission Distance” and the “Assumed Physical Transmission Distance” pertains to the fact that in reality the electricity produced in the generation zone is not transmitted completely the whole “reference transmission distance” (here 1,300 km) within a separate transmission line but fed to the grid at the generation zone and the same amount taken from the grid at the supply zone. The demand for further power plants delivering to the grid is adapted to the supply of our solar power plant. Thus, the real transmission distance of the electricity finally is lower, here called “physical transmission distance” with assumed 600 km.

Table 103. Estimates for Supply Zones and Power Transmission

| Zone         | Supply Power in GW | New 5 GW Transmission Lines | Reference Transmission Distance in km | Assumed Physical Transmission Distance in km |
|--------------|--------------------|-----------------------------|---------------------------------------|----------------------------------------------|
| A1-E         | 0.5                | ---                         | 1,300                                 | 600                                          |
| <b>Total</b> | <b>0.5</b>         | <b>---</b>                  | <b>1,300</b>                          | <b>600</b>                                   |

### 8.2.1.1.1 Scenario A (Photovoltaic) - 500 MW today

Figure 104 shows the necessary PV peak power per demand power in  $\text{GW}_p/\text{GW}$  in dependence on the storage capacity in days.

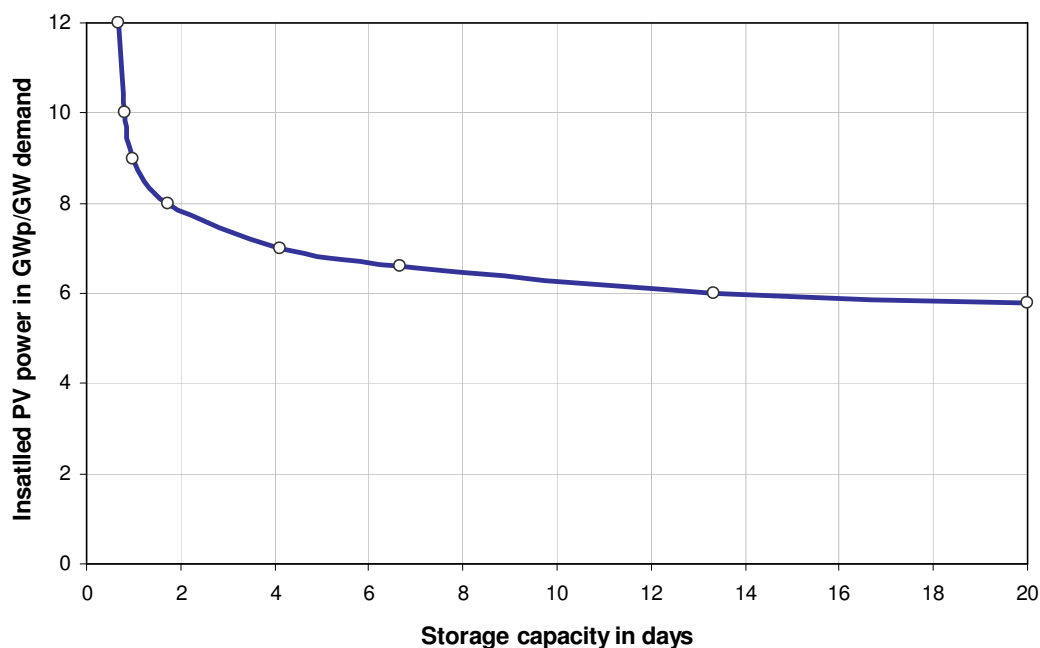


Figure 104. Estimation of Storage demand and PV Installation, assuming 2% transmission losses and 75% storage efficiency

For the storage capacity of one day in the average an installation of about  $9 \text{ GW}_p$  per  $\text{GW}$  demand load are required to maintain the power demand supply also through the night. With higher storage capacities the necessary peak power PV capacity is slightly decreasing.

For storage at the low power levels like the 500 MW here the pumped hydroelectric storage is assumed to be near the user demand, i.e. in Europe. The calculations in Table 104 were made for several power levels and corresponding storage capacities. The variation of the LEC can be seen in Table 105.

Table 104. Technical Results and assumptions for cost calculations (500 MW base load with PV)

| Base load           |                   | 0.5 GW<br>4.38 TWh | 0.5 GW<br>4.38 TWh | 0.5 GW<br>4.38 TWh  | 0.5 GW<br>4.38 TWh  |
|---------------------|-------------------|--------------------|--------------------|---------------------|---------------------|
| <b>Photovoltaic</b> |                   |                    |                    |                     |                     |
| Capacity            | GW <sub>p</sub>   | 2.9                | 3                  | 3.5                 | 4                   |
| Generation          | TWh               | 5.330              | 5.514              | 6.432               | 7.351               |
| Installation costs  | €/kW <sub>p</sub> | 3,048              | 3,026              | 2,925               | 2,839               |
|                     | billion €         | 8.839              | 9.078              | 10.238              | 11.356              |
| Lifetime            | years             | 25                 | 25                 | 25                  | 25                  |
| O&M costs           | billion € p.a.    | 0.194              | 0.200              | 0.225               | 0.250               |
| <b>Transmission</b> |                   |                    |                    |                     |                     |
| Costs               | €/MWh             | 10                 | 10                 | 10                  | 10                  |
| Losses              |                   | 2 %                | 2 %                | 2 %                 | 2 %                 |
| <b>Storage</b>      |                   |                    |                    |                     |                     |
|                     |                   | pumped<br>hydro    | pumped<br>hydro    | pumped<br>hydro     | pumped<br>hydro     |
| Capacity            |                   | 2.02 GW<br>240 GWh | 2.10 GW<br>180 GWh | 2.54 GW<br>49.5 GWh | 2.97 GW<br>20.7 GWh |
| Efficiency          |                   | 75 %               | 75 %               | 75 %                | 75 %                |
| Installation costs  | €/kW              | 2363               | 1900               | 973                 | 798                 |
|                     | billion €         | 4.774              | 3.990              | 2.471               | 2.369               |
| Lifetime            | years             | 40                 | 40                 | 40                  | 40                  |
| O&M costs           | billion € p.a.    | 0.015              | 0.015              | 0.015               | 0.015               |

Table 105. Cost calculations (500 MW base load with PV)

|                                    |                 |                    |                    |                     |                     |
|------------------------------------|-----------------|--------------------|--------------------|---------------------|---------------------|
| <b>Assumptions</b>                 |                 |                    |                    |                     |                     |
| PV Capacity                        | GW <sub>p</sub> | 2.9                | 3                  | 3.5                 | 4                   |
| Storage Capacity                   |                 | 2.02 GW<br>240 GWh | 2.10 GW<br>180 GWh | 2.54 GW<br>49.5 GWh | 2.97 GW<br>20.7 GWh |
| <b>Resulting LEC</b>               |                 |                    |                    |                     |                     |
| Interest rate 6 %                  | €/kWh           | 0.290              | 0.284              | 0.290               | 0.316               |
| Interest rate 8 %                  | €/kWh           | 0.340              | 0.332              | 0.335               | 0.365               |
| <b>LEC Breakdown<br/>for IR=6%</b> |                 |                    |                    |                     |                     |
| PV generation                      |                 | 57.3 %             | 58.1 %             | 55.1 %              | 49.1 %              |
| Transmission                       |                 | 5.3 %              | 5.5 %              | 6.1 %               | 6.2 %               |
| Storage and dumping                |                 | 37.5 %             | 36.4 %             | 38.8 %              | 44.7 %              |

### 8.2.1.1.2 Scenario B (Solar Thermal Power) - 500 MW today

Assumption for storage: Pumped hydro storage near user demand. Collector orientation in Table 106 means East-West.

Table 106. Technical Results and assumption cost calculations (500 MW base load ST)

| Base load           |                        | 0.5 GW<br>4.38 TWh | 0.5 GW<br>4.38 TWh | 0.5 GW<br>4.38 TWh | 0.5 GW<br>4.38 TWh |
|---------------------|------------------------|--------------------|--------------------|--------------------|--------------------|
| <b>ST Power</b>     |                        |                    |                    |                    |                    |
| Capacity            | GW <sub>el</sub>       | 0.9                | 1.0                | 0.85               | 0.75               |
| Field Size          | million m <sup>2</sup> | 16.2               | 18.0               | 20.2               | 17.8               |
| Collector           | orientation            | E-W                | E-W                | E-W                | E-W                |
| Thermal Storage     | GWh <sub>th</sub>      | 41.8               | 46.4               | 52.4               | 46.3               |
|                     | h                      | 18                 | 18                 | 24                 | 24                 |
| Generation          | TWh                    | 5.072              | 5.633              | 5.711              | 5.046              |
| Installation costs  | €/kW <sub>el</sub>     | 4,594              | 4,513              | 5,670              | 5,782              |
|                     | billion €              | 4.135              | 4.513              | 4.819              | 4.336              |
| Lifetime            | years                  | 25                 | 25                 | 25                 | 25                 |
| O&M costs           | billion € p.a.         | 0.120              | 0.131              | 0.140              | 0.126              |
| <b>Transmission</b> |                        |                    |                    |                    |                    |
| Costs               | €/MWh                  | 10                 | 10                 | 10                 | 10                 |
| Losses              |                        | 2 %                | 2 %                | 2 %                | 2 %                |
| <b>Storage</b>      |                        |                    |                    |                    |                    |
|                     |                        | pumped<br>hydro    | pumped<br>hydro    | pumped<br>hydro    | pumped<br>hydro    |
| Capacity            | GW                     | 0.5                | 0.5                | 0.5                | 0.5                |
|                     | GWh                    | 140                | 50                 | 29                 | 62                 |
| Efficiency          |                        | 75 %               | 75 %               | 75 %               | 75 %               |
| Installation costs  | €/kW                   | 4,620              | 2,100              | 1,512              | 2,436              |
|                     | billion €              | 2.310              | 1.050              | 0.756              | 1.218              |
| Lifetime            | years                  | 40                 | 40                 | 40                 | 40                 |
| O&M costs           | billion € p.a.         | 0.004              | 0.004              | 0.001              | 0.002              |

Table 107. Cost calculations (500 MW base load with ST)

|                                |                  |        |        |        |        |
|--------------------------------|------------------|--------|--------|--------|--------|
| <b>Assumptions</b>             |                  |        |        |        |        |
| ST Capacity                    | GW <sub>el</sub> | 0.9    | 1.0    | 0.85   | 0.75   |
| Storage Capacity               | GW               | 0.5    | 0.5    | 0.5    | 0.5    |
|                                | GWh              | 140    | 50     | 29     | 62     |
| <b>Resulting LEC</b>           |                  |        |        |        |        |
| Interest rate 6 %              | €/kWh            | 0.149  | 0.140  | 0.143  | 0.136  |
| Interest rate 8 %              | €/kWh            | 0.172  | 0.160  | 0.163  | 0.157  |
| <b>LEC Breakdown for IR=6%</b> |                  |        |        |        |        |
| ST generation                  |                  | 58.8 % | 61.4 % | 63.5 % | 67.6 % |
| Transmission                   |                  | 8.8 %  | 10.2 % | 10.2 % | 9.6 %  |
| Storage and dumping            |                  | 32.3 % | 28.4 % | 26.3 % | 22.8 % |



## 8.2.1.2 5 GW Base Load Today

### 8.2.1.2.1 Scenario A (Photovoltaic) - 5 GW today

Table 108. Estimates for Supply Zones and Power Transmission

| Zone         | Supply Power in GW | New 5 GW Transmission Lines *) | Reference Transmission Distance in km | Assumed Physical Transmission Distance in km |
|--------------|--------------------|--------------------------------|---------------------------------------|----------------------------------------------|
| A1-E         | 5.0                | 6,000 (6)                      | 1,300                                 | 1,000                                        |
| <b>Total</b> | <b>5.0</b>         | <b>6,000 (6)</b>               | <b>1,300</b>                          | <b>1,000</b>                                 |

\*) Transmission of 30 GW through 6 lines with a capacity of 5 GW each for an assumed physical transmission distance of 1,000 km requires overall 6,000 km new transmission lines. Storage is estimated near the user.

Assumption for Storage: Pumped hydro storage near user demand.

Table 109. Technical Results and assumption cost calculations (5 GW base load with PV)

|                     |                                            |
|---------------------|--------------------------------------------|
| <b>Base load</b>    | <b>5 GW / 43.8 TWh</b>                     |
| <b>Photovoltaic</b> |                                            |
| Capacity            | 33 GW <sub>p</sub>                         |
| Generation          | 60.62 TWh                                  |
| Installation costs  | 1,970 €/kW <sub>p</sub> / 65.010 billion € |
| Lifetime            | 25 years                                   |
| O&M costs           | 1.430 billion € p.a.                       |
| <b>Transmission</b> |                                            |
| Costs               | 6 billion €                                |
| Lifetime            | 25 years                                   |
| O&M costs           | 0.060 billion € p.a.                       |
| Losses              | 4.7 %                                      |
| <b>Storage</b>      | <b>pumped hydro</b>                        |
| Capacity            | 23.65 GW / 820 GWh                         |
| Efficiency          | 75 %                                       |
| Installation costs  | 1185 €/kW / 28.035 billion €               |
| Lifetime            | 40 years                                   |
| O&M costs           | 0.149 billion € p.a.                       |

Table 110. Cost calculations (5 GW base load with PV)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6 %              | 0.207 €/kWh |
| Interest rate 8 %              | 0.243 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| PV generation                  | 52.0 %      |
| Transmission                   | 8.3 %       |
| Storage and dumping            | 39.7 %      |

### 8.2.1.2.2 Scenario B (Solar Thermal Power) - 5 GW today

Table 111. Estimates for Supply Zones and Power Transmission

| Zone         | Supply Power in GW | New 5 GW Transmission Lines *) | Reference Transmission Distance in km | Assumed Physical Transmission Distance in km |
|--------------|--------------------|--------------------------------|---------------------------------------|----------------------------------------------|
| A1-E         | 5.0                | 2,000 (2)                      | 1,300                                 | 1,000                                        |
| <b>Total</b> | <b>5.0</b>         | <b>2,000 (2)</b>               | <b>1,300</b>                          | <b>1,000</b>                                 |

\*) Transmission of 7.3 GW through 2 new lines with unit capacity of 5 GW each with an assumed physical transmission distance of 1,000 km each yields 2,000 km new transmission lines. Storage is estimated to be near the user.

Assumption for Storage: Pumped hydro storage near user demand.

Table 112. Technical Results and assumption cost calculations (5 GW base load with ST)

|                       |                               |
|-----------------------|-------------------------------|
| <b>Base load</b>      | <b>5.0 GW</b>                 |
|                       | <b>43.8 TWh</b>               |
| <b>ST Power</b>       |                               |
| Capacity              | 7.7 GW <sub>el</sub>          |
| Field Size            | 182.6 million m <sup>2</sup>  |
| Collector orientation | E-W                           |
| Thermal Storage       | 475.1 GWh <sub>th</sub>       |
| Generation            | 51.033 TWh                    |
| Installation costs    | 3,841 €/kW <sub>el</sub>      |
|                       | 29.577 billion €              |
| Lifetime              | 25 years                      |
| O&M costs             | 0.858 billion € p.a.          |
| <b>Transmission</b>   |                               |
| Costs                 | 2 billion €                   |
| Lifetime              | 25 years                      |
| O&M costs             | 0.020 billion € p.a.          |
| Losses                | 4.7 %                         |
| <b>Storage</b>        | pumped hydro                  |
| Capacity              | 5.0 GW / 620 GWh              |
| Efficiency            | 75 %                          |
| Installation costs    | 2,436 €/kW / 12.180 billion € |
| Lifetime              | 40 years                      |
| O&M costs             | 0.020 billion € p.a.          |

Table 113. Cost calculations (5 GW base load with ST)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6 %              | 0.095 €/kWh |
| Interest rate 8 %              | 0.111 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| ST generation                  | 64.1 %      |
| Transmission                   | 7.2 %       |
| Storage and dumping            | 28.6 %      |

### 8.2.1.3 10 GW Base Load Today

#### 8.2.1.3.1 Scenario A (Photovoltaic) - 10 GW today

Table 114. Estimates for AC Power Transmission to Near Generation Pumped Storage

| Zone   | Supply Power in GW | New HVAC Transmission Lines in km | Transmission Losses | Investment Costs in billion € |
|--------|--------------------|-----------------------------------|---------------------|-------------------------------|
| A3-A3S | 55.0               | 350                               | 1.5%                | 3.696 billion €               |

Table 115. Estimates for Supply Zones and Power Transmission

| Zone         | Reference and Transmission Distance in km | Transm. Losses | Transm. Capacity in GW | Supply Power in GW | New 5 GW lines and HVDC stations |
|--------------|-------------------------------------------|----------------|------------------------|--------------------|----------------------------------|
| A3S-G        | 3,800                                     | 13.9%          | 10.0                   | 5.0                | 7,600 / 2                        |
| A3S-I        | 4,600                                     | 16.6%          | 5.0                    | 5.0                | 4,600 / 1                        |
| <b>Total</b> | <b>4,200</b>                              | <b>15.3%</b>   | <b>15.0</b>            | <b>10.0</b>        | <b>12,200 / 3</b>                |

Table 116. Technical Results and assumption for cost calculations (10 GW base load with PV)

|                             |                                             |
|-----------------------------|---------------------------------------------|
| <b>Base load</b>            | <b>10 GW / 87.6 TWh</b>                     |
| <b>Photovoltaic</b>         |                                             |
| Capacity                    | 65 GW <sub>p</sub>                          |
| Generation                  | 134.44 TWh                                  |
| Installation costs          | 1,855 €/kW <sub>p</sub> / 120.575 billion € |
| Lifetime                    | 25 years                                    |
| Excess generation           | 12.47 TWh                                   |
| Revenues                    | -0.249 billion € p.a. (0.02 €/kWh)          |
| O&M costs                   | 3.256 billion € p.a.                        |
| <b>Transmission</b>         |                                             |
| Costs                       | 9.38 billion €                              |
| Lifetime                    | 25 years                                    |
| O&M costs                   | 0.094 billion € p.a.                        |
| Losses                      | 1.5% + 15.3%                                |
| <b>Storage</b> pumped hydro |                                             |
| Capacity                    | 42.51 GW / 200 GWh                          |
| Efficiency                  | 75%                                         |
| Installation costs          | 766 €/kW / 32.555 billion €                 |
| Lifetime                    | 40 years                                    |
| O&M costs                   | 0.341 billion € p.a.                        |

Table 117. Cost calculations (10 GW base load with PV)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.180 €/kWh |
| Interest rate 8%               | 0.209 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| PV generation                  | 51.4 %      |
| Transmission                   | 13.3 %      |
| Storage and dumping            | 35.3 %      |

### 8.2.1.3.2 Scenario B (Solar Thermal Power) - 10 GW today

For higher power levels it is useful to use for generation also sites more in the south. Thus, Atar in Mauritania replaced the Kenitra site in Morocco. 20% of the generation should be made at that site. This will need an addition 2,000 km transmission line. This could reduce the storage demand significantly so that it can also be covered by pumped hydroelectric storage power plants.

Table 118. Estimates for Supply Zones and Power Transmission

| Zone         | Supply Power in GW | New 5 GW Transmission Lines (Stations) | Reference Transmission Distance in km | Assumed Physical Transmission Distance in km |
|--------------|--------------------|----------------------------------------|---------------------------------------|----------------------------------------------|
| A1b-A1       | 2.0                | 2,000 (1)                              | 2,000                                 | 2,000                                        |
| A1-E         | 8.0                | 2,600 (3)                              | 1,300                                 | 1,200                                        |
| A1-F         | 3.0                | ---                                    | 2,500                                 | 1,700                                        |
| <b>Total</b> | <b>10.0</b>        | <b>9,800 (4)</b>                       | <b>-</b>                              | <b>~ 1,600</b>                               |

Table 119. Technical Results and assumption for cost calculations (10 GW base load with ST)

|                       |                                   |
|-----------------------|-----------------------------------|
| <b>Base load</b>      | <b>10.0 GW</b><br><b>87.6 TWh</b> |
| <b>ST Power</b>       |                                   |
| Capacity              | 15.5 GW <sub>el</sub>             |
| Field Size            | 367.5 million m <sup>2</sup>      |
| Collector orientation | E-W                               |
| Thermal Storage       | 956.4 GWh <sub>th</sub>           |
| Generation            | 102.86 TWh                        |
| Installation costs    | 3,378 €/kW <sub>el</sub>          |
|                       | 52.359 billion €                  |
| Lifetime              | 25 years                          |
| O&M costs             | 1.518 billion € p.a.              |
| <b>Transmission</b>   |                                   |
| Costs                 | 5.74 billion €                    |
| Lifetime              | 25 years                          |
| O&M costs             | 0.057 billion € p.a.              |
| Losses                | 6.7%                              |
| <b>Storage</b>        | pumped hydro                      |
| Capacity              | 10.0 GW / 680 GWh                 |
| Efficiency            | 75%                               |
| Installation costs    | 1,652 €/kW / 16.52 billion €      |
| Lifetime              | 40 years                          |
| O&M costs             | 0.041 billion € p.a.              |

Table 120. Cost calculations (10 GW base load with ST)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.083 €/kWh |
| Interest rate 8%               | 0.096 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| ST generation                  | 65.9%       |
| Transmission                   | 11.4%       |
| Storage and dumping            | 22.7%       |

### 8.2.1.4 100 GW Base Load Today

#### 8.2.1.4.1 Scenario A (Photovoltaic) - 100 GW today

Table 121. Estimates for AC Power Transmission to Near Generation Pumped Storage

| Zone   | Supply Power in GW | New HVAC Transmission Lines in km | Transmission Losses | Investment Costs in billion € |
|--------|--------------------|-----------------------------------|---------------------|-------------------------------|
| A3-A3S | 550                | 350                               | 1.5%                | 32.34 billion €               |

Table 122. Estimates for Supply Zones and Power Transmission

| Zone         | Reference and Transmission Distance in km | Transm. Losses | Transm. Capacity in GW | Supply Power in GW | New 5 GW lines and HVDC stations |
|--------------|-------------------------------------------|----------------|------------------------|--------------------|----------------------------------|
| A3S-E        | 5,100                                     | 18.2 %         | 15.0                   | 12.3               | 15,300 / 3.0                     |
| A3S-G1       | 3,800                                     | 13.2 %         | 105.0                  | 91.1               | 79,800 / 10.5                    |
| G1-G         | 0                                         | 0.7 %          | 5.0                    | 5.0                | 0 / 0.5                          |
| G1-B         | 2,100                                     | 7.6 %          | 10.0                   | 9.2                | 4,200 / 1.0                      |
| G1-D         | 1,700                                     | 6.3 %          | 25.0                   | 23.4               | 8,500 / 2.5                      |
| G1-F         | 1,800                                     | 6.6 %          | 20.0                   | 18.7               | 7,200 / 2.0                      |
| G1-I         | 800                                       | 3.3 %          | 15.0                   | 14.5               | 2,400 / 1.5                      |
| G1-P         | 1,000                                     | 4.0 %          | 20.0                   | 19.2               | 4,000 / 2.0                      |
| <b>Total</b> | <b>5,060</b>                              | <b>18.1 %</b>  | <b>120.0</b>           | <b>100.0</b>       | <b>121,400 / 23</b>              |



Table 123. Technical Results and assumption for cost calculations (100 GW base load with PV)

| <b>Base load</b>    |                                            | <b>100 GW / 876 TWh</b> |
|---------------------|--------------------------------------------|-------------------------|
| <b>Photovoltaic</b> |                                            |                         |
| Capacity            |                                            | 653 GW <sub>p</sub>     |
| Generation          |                                            | 1350.56 TWh             |
| Installation costs  | 1,408 €/kW <sub>p</sub> / 991.42 billion € |                         |
| Lifetime            |                                            | 25 years                |
| Excess generation   |                                            | 100.76 TWh              |
| Revenues            | -2.015 billion € p.a. (0.02 €/kWh)         |                         |
| O&M costs           |                                            | 24.824 billion € p.a.   |
| <b>Transmission</b> |                                            |                         |
| Costs               |                                            | 77.675 billion €        |
| Lifetime            |                                            | 25 years                |
| O&M costs           |                                            | 0.777 billion € p.a.    |
| Losses              |                                            | 1.5% + 18.1%            |
| <b>Storage</b>      |                                            | <b>pumped hydro</b>     |
| Capacity            |                                            | 424.77 GW / 3000 GWh    |
| Efficiency          |                                            | 75%                     |
| Installation costs  | 799 €/kW / 339.336 billion €               |                         |
| Lifetime            |                                            | 40 years                |
| O&M costs           |                                            | 3.500 billion € p.a.    |

Table 124. Cost calculations (100 GW base load with PV)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.146 €/kWh |
| Interest rate 8%               | 0.170 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| PV generation                  | 48.1%       |
| Transmission                   | 11.6%       |
| Storage and dumping            | 40.2%       |

#### 8.2.1.4.2 Scenario B (Solar Thermal Power) - 100 GW today

Table 125. Estimates for Supply Zones and Power Transmission

| Zone         | Reference<br>and<br>Transmission<br>Distance<br>in km | Transm.<br>Losses | Transm.<br>Capacity<br>in GW | Supply<br>Power<br>in GW | New 5 GW<br>lines and<br>HVDC stations |
|--------------|-------------------------------------------------------|-------------------|------------------------------|--------------------------|----------------------------------------|
| A3-E         | 5,100                                                 | 18.2 %            | 25.0                         | 20.5                     | 25,500 / 5.0                           |
| A3-G1        | 3,800                                                 | 13.2 %            | 115.0                        | 99.8                     | 87,400 / 11.5                          |
| G1-G         | 0                                                     | 0.7 %             | 5.0                          | 5.0                      | 0 / 0.5                                |
| G1-B         | 2,100                                                 | 7.6 %             | 10.0                         | 9.2                      | 4,200 / 1.0                            |
| G1-D         | 1,700                                                 | 6.3 %             | 25.0                         | 23.4                     | 8,500 / 2.5                            |
| G1-F         | 1,800                                                 | 6.6 %             | 20.0                         | 18.7                     | 7,200 / 2.0                            |
| G1-I         | 800                                                   | 3.3 %             | 15.0                         | 14.5                     | 2,400 / 1.5                            |
| G1-P         | 1,000                                                 | 4.0 %             | 20.0                         | 19.2                     | 4,000 / 2.0                            |
| G1-S         | 1,400                                                 | 5.3 %             | 5.0                          | 4.7                      | 1,400 / 0.5                            |
| <b>Total</b> | <b>5,020</b>                                          | <b>18.0 %</b>     | <b>140.0</b>                 | <b>~115.0</b>            | <b>140,600 / 27</b>                    |

Table 126. Technical Results and assumption for cost calculations (100 GW base load with ST)

|                       |                                   |
|-----------------------|-----------------------------------|
| <b>Base load</b>      | <b>100.0 GW</b><br><b>876 TWh</b> |
| <b>ST Power</b>       |                                   |
| Capacity              | 150 GW <sub>el</sub>              |
| Field Size            | 3,556.5 million m <sup>2</sup>    |
| Collector orientation | E-W                               |
| Thermal Storage       | 9,255 GWh <sub>th</sub>           |
| Generation            | 1142.5 TWh                        |
| Installation costs    | 2,851 €/kW <sub>el</sub>          |
|                       | 427.637 billion €                 |
| Lifetime              | 25 years                          |
| O&M costs             | 12.401 billion € p.a.             |
| <b>Transmission</b>   |                                   |
| Costs                 | 52.300 billion €                  |
| Lifetime              | 25 years                          |
| O&M costs             | 0.523 billion € p.a.              |
| Losses                | 18.0%                             |
| <b>Storage</b>        | pumped hydro                      |
| Capacity              | 31.8 GW / 255 GWh                 |
| Efficiency            | 75%                               |
| Installation costs    | 812 €/kW / 25.830 billion €       |
| Lifetime              | 40 years                          |
| O&M costs             | 0.074 billion € p.a.              |

Table 127. Cost calculations (100 GW base load with ST)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.060 €/kWh |
| Interest rate 8%               | 0.069 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| ST generation                  | 67.3%       |
| Transmission                   | 20.9%       |
| Storage and dumping            | 11.8%       |

### 8.2.1.5 150 GW Base Load Today (Full Supply)

#### 8.2.1.5.1 Scenario A (Photovoltaic) - 150 GW today

Table 128. Estimates for AC Power Transmission to Near Generation Pumped Storage

| Zone   | Supply Power in GW | New HVAC Transmission Lines in km | Transmission Losses | Investment Costs in billion € |
|--------|--------------------|-----------------------------------|---------------------|-------------------------------|
| A3-A3S | 841                | 350                               | 1.5 %               | 48.26 billion €               |

Table 129. Estimates for Supply Zones and Power Transmission

| Zone         | Reference and Transmission Distance in km | Transm. Losses | Transm. Capacity in GW | Supply Power in GW | New 5 GW lines and HVDC stations |
|--------------|-------------------------------------------|----------------|------------------------|--------------------|----------------------------------|
| A3S-E        | 5,100                                     | 18.2 %         | 20.0                   | 16.4               | 20,400 / 4.0                     |
| A3S-G1       | 3,800                                     | 13.2 %         | 170.0                  | 147.5              | 129,200 / 17.0                   |
| G1-G         | 0                                         | 0.7 %          | 5.0                    | 5.0                | 0 / 0.5                          |
| G1-B         | 2,100                                     | 7.6 %          | 10.0                   | 9.2                | 4,200 / 1.0                      |
| G1-D         | 1,700                                     | 6.3 %          | 30.0                   | 28.1               | 10,200 / 2.5                     |
| G1-F         | 1,800                                     | 6.6 %          | 30.0                   | 28.0               | 10,800 / 3.5                     |
| G1-I         | 800                                       | 3.3 %          | 20.0                   | 19.3               | 3,200 / 2.0                      |
| G1-P         | 1,000                                     | 4.0 %          | 20.0                   | 19.2               | 4,000 / 2.5                      |
| G1-S         | 1,400                                     | 5.3 %          | 5.0                    | 4.7                | 1,400 / 0.5                      |
| G1-U         | 2,700                                     | 9.6 %          | 25.0                   | 22.6               | 13,500 / 3.0                     |
| <b>Total</b> | <b>5,180</b>                              | <b>18.5 %</b>  | <b>190.0</b>           | <b>152.0</b>       | <b>196,900 / 36</b>              |

Table 130. Technical Results and assumption for cost calculations (150 GW base load with PV)

|                             |                                           |
|-----------------------------|-------------------------------------------|
| <b>Base load</b>            | <b>150 GW / 876 TWh</b>                   |
| <b>Photovoltaic</b>         |                                           |
| Capacity                    | 997 GW <sub>p</sub>                       |
| Generation                  | 2,062 TWh                                 |
| Installation costs          | 1,338 €/kW <sub>p</sub> / 1,334 billion € |
| Lifetime                    | 25 years                                  |
| Excess generation           | 181.5 TWh                                 |
| Revenues                    | -3.630 billion € p.a. (0.02 €/kWh)        |
| O&M costs                   | 36.018 billion € p.a.                     |
| <b>Transmission</b>         |                                           |
| Costs                       | 118.968 billion €                         |
| Lifetime                    | 25 years                                  |
| O&M costs                   | 1.190 billion € p.a.                      |
| Losses                      | 1.5 % + 18.5 %                            |
| <b>Storage</b> pumped hydro |                                           |
| Capacity                    | 651.10 GW / 3,500 GWh                     |
| Efficiency                  | 75%                                       |
| Installation costs          | 775 €/kW / 504.767 billion €              |
| Lifetime                    | 40 years                                  |
| O&M costs                   | 5.262 billion € p.a.                      |

Table 131. Cost calculations (150 GW base load with PV)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.142 €/kWh |
| Interest rate 8%               | 0.165 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| PV generation                  | 46.8%       |
| Transmission                   | 15.0%       |
| Storage and dumping            | 38.2%       |

### 8.2.1.5.2 Scenario B (Solar Thermal Power) - 150 GW today

Table 132. Estimates for Supply Zones and Power Transmission

| Zone         | Reference and Transmission Distance in km | Transm. Losses | Transm. Capacity in GW | Supply Power in GW | New 5 GW lines and HVDC stations |
|--------------|-------------------------------------------|----------------|------------------------|--------------------|----------------------------------|
| A3-E         | 5,100                                     | 18.2 %         | 20.0                   | 16.4               | 20,400 / 4.0                     |
| A3-G1        | 3,800                                     | 13.2 %         | 190.0                  | 164.9              | 144,400 / 19.0                   |
| G1-G         | 0                                         | 0.7 %          | 5.0                    | 5.0                | 0 / 0.5                          |
| G1-B         | 2,100                                     | 7.6 %          | 10.0                   | 9.2                | 4,200 / 1.0                      |
| G1-D         | 1,700                                     | 6.3 %          | 35.0                   | 32.8               | 11,900 / 2.5                     |
| G1-F         | 1,800                                     | 6.6 %          | 35.0                   | 32.7               | 12,600 / 3.5                     |
| G1-I         | 800                                       | 3.3 %          | 20.0                   | 19.3               | 3,200 / 2.0                      |
| G1-P         | 1,000                                     | 4.0 %          | 25.0                   | 24.0               | 5,000 / 2.5                      |
| G1-S         | 1,400                                     | 5.3 %          | 5.0                    | 4.7                | 1,400 / 0.5                      |
| G1-U         | 2,700                                     | 9.6 %          | 30.0                   | 27.1               | 16,200 / 3.0                     |
| <b>Total</b> | <b>5,220</b>                              | <b>18.6 %</b>  | <b>210.0</b>           | <b>~170.0</b>      | <b>219,300 / 40</b>              |

Table 133. Technical Results and assumption for cost calculations (150 GW base load with ST)

|                       |                                     |
|-----------------------|-------------------------------------|
| <b>Base load</b>      | <b>150.0 GW</b><br><b>1,314 TWh</b> |
| <b>ST Power</b>       |                                     |
| Capacity              | 220 GW <sub>el</sub>                |
| Field Size            | 5,216 million m <sup>2</sup>        |
| Collector orientation | E-W                                 |
| Thermal Storage       | 13,574 GWh <sub>th</sub>            |
| Generation            | 1,757 TWh                           |
| Installation costs    | 2,787 €/kW <sub>el</sub>            |
|                       | 613.146 billion €                   |
| Lifetime              | 25 years                            |
| O&M costs             | 17.781 billion € p.a.               |
| <b>Transmission</b>   |                                     |
| Costs                 | 78.185 billion €                    |
| Lifetime              | 25 years                            |
| O&M costs             | 0.782 billion € p.a.                |
| Losses                | 18.6%                               |
| <b>Storage</b>        | <b>pumped hydro</b>                 |
| Capacity              | 47.4 GW / 370 GWh                   |
| Efficiency            | 75%                                 |
| Installation costs    | 809 €/kW / 38.360 billion €         |
| Lifetime              | 40 years                            |
| O&M costs             | 0.106 billion € p.a.                |

Table 134. Cost calculations (150 GW base load with ST)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.057 €/kWh |
| Interest rate 8%               | 0.066 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| ST generation                  | 65.3%       |
| Transmission                   | 19.6%       |
| Storage and dumping            | 15.1%       |

## 8.2.2 Base Load Demand 2020/2030

The technical estimations for the power transmission are the same as for the state-of-the art scenarios.

### 8.2.2.1 500 MW Base Load in 2020/2030

#### 8.2.2.1.1 Scenario A (Photovoltaic) - 500 MW in 2020/2030

Table 135. Technical Results and assumption for cost calculations (500 MW base load with PV)

|                     |                                           |
|---------------------|-------------------------------------------|
| <b>Base load</b>    | <b>0.5 GW / 4.38 TWh</b>                  |
| <b>Photovoltaic</b> |                                           |
| Capacity            | 3 GW <sub>p</sub>                         |
| Generation          | 5.789 TWh                                 |
| Installation costs  | 1,253 €/kW <sub>p</sub> / 3.759 billion € |
| Lifetime            | 25 years                                  |
| O&M costs           | 0.056 billion € p.a.                      |
| <b>Transmission</b> |                                           |
| Costs               | 7 €/MWh                                   |
| Losses              | 1.5%                                      |
| <b>Storage</b>      | <b>pumped hydro</b>                       |
| Capacity            | 2.25 GW / 60 GWh                          |
| Efficiency          | 85%                                       |
| Installation costs  | 920 €/kW / 2.07 billion €                 |
| Lifetime            | 40 years                                  |
| O&M costs           | 0.010 billion € p.a.                      |

Table 136. Cost calculations (500 MW base load with PV)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.123 €/kWh |
| Interest rate 8%               | 0.144 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| PV generation                  | 49.3%       |
| Transmission                   | 8.2%        |
| Storage and dumping            | 42.5%       |



### 8.2.2.1.2 Scenario B (Solar Thermal Power) - 500 MW in 2020/2030

Table 137. Technical Results and assumption for cost calculations (500 MW base load with ST)

|                       |                                             |
|-----------------------|---------------------------------------------|
| <b>Base load</b>      | <b>0.5 GW<br/>4.38 TWh</b>                  |
| <b>ST Power</b>       |                                             |
| Capacity              | 0.73 GW <sub>el</sub>                       |
| Field Size            | 16.4 million m <sup>2</sup>                 |
| Collector orientation | E-W                                         |
| Thermal Storage       | 42.8 GWh <sub>th</sub>                      |
| Generation            | 4.914 TWh                                   |
| Installation costs    | 3,897 €/kW <sub>el</sub><br>2.845 billion € |
| Lifetime              | 25 years                                    |
| O&M costs             | 0.082 billion € p.a.                        |
| <b>Transmission</b>   |                                             |
| Costs                 | 7 €/MWh                                     |
| Losses                | 1.5%                                        |
| <b>Storage</b>        | pumped hydro                                |
| Capacity              | 0.5 GW / 70 GWh                             |
| Efficiency            | 85%                                         |
| Installation costs    | 2,280 €/kW / 1.140 billion €                |
| Lifetime              | 40 years                                    |
| O&M costs             | 0.001 billion € p.a.                        |

Table 138. Cost calculations (500 MW base load with ST)

|                                    |             |
|------------------------------------|-------------|
| <b>Resulting LEC</b>               |             |
| Interest rate 6%                   | 0.095 €/kWh |
| Interest rate 8%                   | 0.110 €/kWh |
| <b>LEC Breakdown<br/>for IR=6%</b> |             |
| ST generation                      | 65.3%       |
| Transmission                       | 9.1%        |
| Storage and dumping                | 25.5%       |

### 8.2.2.2 5 GW Base Load in 2020/2030

The technical estimations for the power transmission are the same as for the state-of-the art scenarios.

#### 8.2.2.2.1 Scenario A (Photovoltaic) - 5 GW in 2020/2030

Table 139. Technical Results and assumption for cost calculations (5 GW base load with PV)

|                     |                                            |
|---------------------|--------------------------------------------|
| <b>Base load</b>    | <b>5 GW / 43.8 TWh</b>                     |
| <b>Photovoltaic</b> |                                            |
| Capacity            | 30 GW <sub>p</sub>                         |
| Generation          | 67.866 TWh                                 |
| Installation costs  | 1,098 €/kW <sub>p</sub> / 32.940 billion € |
| Lifetime            | 25 years                                   |
| O&M costs           | 0.494 billion € p.a.                       |
| <b>Transmission</b> |                                            |
| Costs               | 5 billion €                                |
| Lifetime            | 25 years                                   |
| O&M costs           | 0.050 billion € p.a.                       |
| Losses              | 3.5%                                       |
| <b>Storage</b>      | <b>pumped hydro</b>                        |
| Capacity            | 21.93 GW / 700 GWh                         |
| Efficiency          | 85%                                        |
| Installation costs  | 983 €/kW / 21.558 billion €                |
| Lifetime            | 40 years                                   |
| O&M costs           | 0.100 billion € p.a.                       |

Table 140. Cost calculations (5 GW base load with PV)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.115 €/kWh |
| Interest rate 8%               | 0.137 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| PV generation                  | 39.5%       |
| Transmission                   | 10.1%       |
| Storage and dumping            | 50.4%       |

### 8.2.2.2.2 Scenario B (Solar Thermal Power) - 5 GW in 2020/2030

Table 141. Technical Results and assumption for cost calculations (5 GW base load with ST)

|                       |                                  |
|-----------------------|----------------------------------|
| <b>Base load</b>      | <b>5.0 GW</b><br><b>43.8 TWh</b> |
| <b>ST Power</b>       |                                  |
| Capacity              | 7.5 GW <sub>el</sub>             |
| Field Size            | 168.9 million m <sup>2</sup>     |
| Collector orientation | E-W                              |
| Thermal Storage       | 439.7 GWh <sub>th</sub>          |
| Generation            | 50.483 TWh                       |
| Installation costs    | 3,256 €/kW <sub>el</sub>         |
|                       | 24.421 billion €                 |
| Lifetime              | 25 years                         |
| O&M costs             | 0.708 billion € p.a.             |
| <b>Transmission</b>   |                                  |
| Costs                 | 2 billion €                      |
| Lifetime              | 25 years                         |
| O&M costs             | 0.020 billion € p.a.             |
| Losses                | 3.5%                             |
| <b>Storage</b>        | <b>pumped hydro</b>              |
| Capacity              | 5.0 GW / 605 GWh                 |
| Efficiency            | 85%                              |
| Installation costs    | 2,052 €/kW / 10.26 billion €     |
| Lifetime              | 40 years                         |
| O&M costs             | 0.014 billion € p.a.             |

Table 142. Cost calculations (5 GW base load with ST)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.080 €/kWh |
| Interest rate 8%               | 0.093 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| ST generation                  | 65.1%       |
| Transmission                   | 7.3%        |
| Storage and dumping            | 27.6%       |

### 8.2.2.3 10 GW Base Load in 2020/2030

#### 8.2.2.3.1 Scenario A (Photovoltaic) - 10 GW in 2020/2030

Table 143. Estimates for AC Power Transmission to Near Generation Pumped Storage

| Zone   | Supply Power in GW | New HVAC Transmission Lines in km | Transmission Losses | Investment Costs in billion € |
|--------|--------------------|-----------------------------------|---------------------|-------------------------------|
| A3-A3S | 46.0               | 350                               | 1.5%                | 2.192 billion €               |

Table 144. Estimates for Supply Zones and Power Transmission.

| Zone         | Reference and Transmission Distance in km | Transm. Losses | Transm. Capacity in GW | Supply Power in GW | New 5 GW lines and HVDC stations |
|--------------|-------------------------------------------|----------------|------------------------|--------------------|----------------------------------|
| A3S-G        | 3,800                                     | 10.5%          | 6.5                    | 5.0                | 3,800 / 1                        |
| A3S-I        | 4,600                                     | 12.5%          | 6.5                    | 5.0                | 4,600 / 1                        |
| <b>Total</b> | <b>4,200</b>                              | <b>11.5%</b>   | <b>13.0</b>            | <b>10.0</b>        | <b>8,400 / 2</b>                 |

Table 145. Technical Results and assumption for cost calculations (10 GW base load with PV)

|                     |                                            |
|---------------------|--------------------------------------------|
| <b>Base load</b>    | <b>10 GW / 87.6 TWh</b>                    |
| <b>Photovoltaic</b> |                                            |
| Capacity            | 55 GW <sub>p</sub>                         |
| Generation          | 113.75 TWh                                 |
| Installation costs  | 1,011 €/kW <sub>p</sub> / 55.605 billion € |
| Lifetime            | 25 years                                   |
| Excess generation   | 10.20 TWh                                  |
| Revenues            | -0.255 billion € p.a. (0.025 €/kWh)        |
| O&M costs           | 1.112 billion € p.a.                       |
| <b>Transmission</b> |                                            |
| Costs               | 6.112 billion €                            |
| Lifetime            | 25 years                                   |
| O&M costs           | 0.061 billion € p.a.                       |
| Losses              | 1.5% + 11.5%                               |
| <b>Storage</b>      | <b>pumped hydro</b>                        |
| Capacity            | 36.86 GW / 230 GWh                         |
| Efficiency          | 85%                                        |
| Installation costs  | 675 €/kW / 24.876 billion €                |
| Lifetime            | 40 years                                   |
| O&M costs           | 0.221 billion € p.a.                       |

Table 146. Cost calculations (10 GW base load with PV)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.087 €/kWh |
| Interest rate 8%               | 0.103 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| PV generation                  | 52.6%       |
| Transmission                   | 13.9%       |
| Storage and dumping            | 33.5%       |

### 8.2.2.3.2 Scenario B (Solar Thermal Power) - 10 GW in 2020/2030

Table 147. Technical Results and assumption for cost calculations (10 GW base load with ST)

|                       |                                              |
|-----------------------|----------------------------------------------|
| <b>Base load</b>      | <b>10.0 GW</b><br><b>87.6 TWh</b>            |
| <b>ST Power</b>       |                                              |
| Capacity              | 15.1 GW <sub>el</sub>                        |
| Field Size            | 340.1 million m <sup>2</sup>                 |
| Collector orientation | E-W                                          |
| Thermal Storage       | 885.2 GWh <sub>th</sub>                      |
| Generation            | 100.2 TWh                                    |
| Installation costs    | 3,020 €/kW <sub>el</sub><br>45.598 billion € |
| Lifetime              | 25 years                                     |
| O&M costs             | 1.322 billion € p.a.                         |
| <b>Transmission</b>   |                                              |
| Costs                 | 5.74 billion €                               |
| Lifetime              | 25 years                                     |
| O&M costs             | 0.057 billion € p.a.                         |
| Losses                | 5.0%                                         |
| <b>Storage</b>        | pumped hydro                                 |
| Capacity              | 10.0 GW / 530 GWh                            |
| Efficiency            | 85%                                          |
| Installation costs    | 1,236 €/kW / 12.36 billion €                 |
| Lifetime              | 40 years                                     |
| O&M costs             | 0.028 billion € p.a.                         |

Table 148. Cost calculations (10 GW base load with ST)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.071 €/kWh |
| Interest rate 8%               | 0.083 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| ST generation                  | 68.5%       |
| Transmission                   | 11.5%       |
| Storage and dumping            | 20.0%       |

## 8.2.2.4 100 GW Base Load in 2020/2030

### 8.2.2.4.1 Scenario A (Photovoltaic) - 100 GW in 2020/2030

Table 149. Estimates for AC Power Transmission to near Generation Pumped Storage

| Zone   | Supply Power in GW | New HVAC Transmission Lines in km | Transmission Losses | Investment Costs in billion € |
|--------|--------------------|-----------------------------------|---------------------|-------------------------------|
| A3-A3S | 467.0              | 350                               | 1.5%                | 19.401 billion €              |

Table 150. Estimates for Supply Zones and Power Transmission

| Zone         | Reference and Transmission Distance in km | Transm. Losses | Transm. Capacity in GW | Supply Power in GW | New 6.5 GW lines and HVDC stations |
|--------------|-------------------------------------------|----------------|------------------------|--------------------|------------------------------------|
| A3S-E        | 5,100                                     | 13.8%          | 13.0                   | 11.2               | 10,200 / 2.0                       |
| A3S-G1       | 3,800                                     | 10.0%          | 104.0                  | 93.6               | 60,800 / 8.0                       |
| G1-G         | 0                                         | 0.5%           | 6.5                    | 6.5                | 0 / 0.5                            |
| G1-B         | 2,100                                     | 5.8%           | 6.5                    | 6.1                | 2,100 / 0.5                        |
| G1-D         | 1,700                                     | 4.8%           | 26.0                   | 24.8               | 6,800 / 2.0                        |
| G1-F         | 1,800                                     | 5.0%           | 19.5                   | 18.5               | 5,400 / 1.5                        |
| G1-I         | 800                                       | 2.5%           | 13.0                   | 12.7               | 1,600 / 1.0                        |
| G1-P         | 1,000                                     | 3.0%           | 19.5                   | 18.9               | 3,000 / 1.5                        |
| G1-S         | 1,400                                     | 4.0%           | 6.5                    | 6.2                | 1,400 / 0.5                        |
| <b>Total</b> | <b>5,070</b>                              | <b>13.7%</b>   | <b>117.0</b>           | <b>~105.0</b>      | <b>91,300 / 18</b>                 |

Table 151. Technical Results and assumption for cost calculations (100 GW base load with PV)

|                             |                                           |
|-----------------------------|-------------------------------------------|
| <b>Base load</b>            | <b>100 GW / 876 TWh</b>                   |
| <b>Photovoltaic</b>         |                                           |
| Capacity                    | 553 GW <sub>p</sub>                       |
| Generation                  | 1143.74 TWh                               |
| Installation costs          | 698 €/kW <sub>p</sub> / 385.994 billion € |
| Lifetime                    | 25 years                                  |
| Excess generation           | 86.74 TWh                                 |
| Revenues                    | -2.169 billion € p.a. (0.025 €/kWh)       |
| O&M costs                   | 5.551 billion € p.a.                      |
| <b>Transmission</b>         |                                           |
| Costs                       | 54.507 billion €                          |
| Lifetime                    | 25 years                                  |
| O&M costs                   | 0.545 billion € p.a.                      |
| Losses                      | 1.5% + 13.7%                              |
| <b>Storage</b> pumped hydro |                                           |
| Capacity                    | 369.02 GW / 3,000 GWh                     |
| Efficiency                  | 85%                                       |
| Installation costs          | 698 €/kW / 257.411 billion €              |
| Lifetime                    | 40 years                                  |
| O&M costs                   | 2.258 billion € p.a.                      |

Table 152. Cost calculations (100 GW base load with PV)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.068 €/kWh |
| Interest rate 8%               | 0.081 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| PV generation                  | 45.7%       |
| Transmission                   | 15.0%       |
| Storage and dumping            | 39.3%       |



#### 8.2.2.4.2 Scenario B (Solar Thermal Power) - 100 GW in 2020/2030

Table 153. Estimates for Supply Zones and Power Transmission

| Zone         | Reference and Transmission Distance in km | Transm. Losses | Transm. Capacity in GW | Supply Power in GW | New 6.5 GW lines and HVDC stations |
|--------------|-------------------------------------------|----------------|------------------------|--------------------|------------------------------------|
| A3-E         | 5,100                                     | 13.8%          | 19.5                   | 16.8               | 15,300 / 3.0                       |
| A3-G1        | 3,800                                     | 10.0%          | 110.5                  | 101.9              | 64,600 / 8.5                       |
| G1-G         | 0                                         | 0.5%           | 6.5                    | 6.5                | 0 / 0.5                            |
| G1-B         | 2,100                                     | 5.8%           | 10.5                   | 9.9                | 3,400 / 1.0                        |
| G1-D         | 1,700                                     | 4.8%           | 26.0                   | 24.8               | 6,800 / 2.0                        |
| G1-F         | 1,800                                     | 5.0%           | 23.0                   | 21.9               | 6,400 / 2.0                        |
| G1-I         | 800                                       | 2.5%           | 13.0                   | 12.7               | 1,600 / 1.0                        |
| G1-P         | 1,000                                     | 3.0%           | 19.5                   | 18.9               | 3,000 / 1.5                        |
| G1-S         | 1,400                                     | 4.0%           | 6.5                    | 6.2                | 1,400 / 0.5                        |
| <b>Total</b> | <b>5,120</b>                              | <b>13.8%</b>   | <b>130.0</b>           | <b>~115.0</b>      | <b>102,500 / 20</b>                |

Table 154. Technical Results and assumption for cost calculations (100 GW base load with ST)

|                       |                                   |
|-----------------------|-----------------------------------|
| <b>Base load</b>      | <b>100.0 GW</b><br><b>876 TWh</b> |
| <b>ST Power</b>       |                                   |
| Capacity              | 138 GW <sub>el</sub>              |
| Field Size            | 3,107.8 million m <sup>2</sup>    |
| Collector orientation | E-W                               |
| Thermal Storage       | 8,089 GWh <sub>th</sub>           |
| Generation            | 1,102.5 TWh                       |
| Installation costs    | 2,677 €/kW <sub>el</sub>          |
|                       | 369.369 billion €                 |
| Lifetime              | 25 years                          |
| O&M costs             | 10.712 billion € p.a.             |
| <b>Transmission</b>   |                                   |
| Costs                 | 39.055 billion €                  |
| Lifetime              | 25 years                          |
| O&M costs             | 0.391 billion € p.a.              |
| Losses                | 13.8%                             |
| <b>Storage</b>        | pumped hydro                      |
| Capacity              | 31.9 GW / 255 GWh                 |
| Efficiency            | 85%                               |
| Installation costs    | 696 €/kW / 22.200 billion €       |
| Lifetime              | 40 years                          |
| O&M costs             | 0.050 billion € p.a.              |

Table 155. Cost calculations (100 GW base load with ST)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.051 €/kWh |
| Interest rate 8%               | 0.059 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| ST generation                  | 70.6%       |
| Transmission                   | 17.5%       |
| Storage and dumping            | 11.9%       |

## 8.2.2.5 150 GW Base Load in 2020/2030 (Full Supply)

### 8.2.2.5.1 Scenario A (Photovoltaic) - 150 GW in 2020/2030

Table 156. Estimates for AC Power Transmission to Near Generation Pumped Storage

| Zone   | Supply Power in GW | New HVAC Transmission Lines in km | Transmission Losses | Investment Costs in billion € |
|--------|--------------------|-----------------------------------|---------------------|-------------------------------|
| A3-A3S | 714.0              | 350                               | 1.5%                | 28.946 billion €              |

Table 157. Estimates for Supply Zones and Power Transmission

| Zone         | Reference and Transmission Distance in km | Transm. Losses | Transm. Capacity in GW | Supply Power in GW | New 6.5 GW lines and HVDC stations |
|--------------|-------------------------------------------|----------------|------------------------|--------------------|------------------------------------|
| A3S-E        | 5,100                                     | 13.8%          | 19.5                   | 16.8               | 15,300 / 3.0                       |
| A3S-G1       | 3,800                                     | 10.0%          | 156.0                  | 140.4              | 91,200 / 12.0                      |
| G1-G         | 0                                         | 0.5%           | 6.5                    | 6.5                | 0 / 0.5                            |
| G1-B         | 2,100                                     | 5.8%           | 13.0                   | 12.3               | 4,200 / 1.0                        |
| G1-D         | 1,700                                     | 4.8%           | 26.0                   | 24.8               | 6,800 / 2.0                        |
| G1-F         | 1,800                                     | 5.0%           | 26.0                   | 24.7               | 7,200 / 2.0                        |
| G1-I         | 800                                       | 2.5%           | 19.5                   | 19.0               | 2,400 / 1.5                        |
| G1-P         | 1,000                                     | 6.0%           | 19.5                   | 18.9               | 3,000 / 1.5                        |
| G1-S         | 1,400                                     | 4.0%           | 6.5                    | 6.2                | 1,400 / 0.5                        |
| G1-U         | 2,700                                     | 7.3%           | 26                     | 24.1               | 10,800 / 2                         |
| <b>Total</b> | <b>5,270</b>                              | <b>14.2%</b>   | <b>175.5</b>           | <b>153.0</b>       | <b>142,300 / 26</b>                |

Table 158. Technical Results and assumption for cost calculations (150 GW base load with PV)

|                     |                                           |
|---------------------|-------------------------------------------|
| <b>Base load</b>    | <b>150 GW / 1,314 TWh</b>                 |
| <b>Photovoltaic</b> |                                           |
| Capacity            | 846 GW <sub>p</sub>                       |
| Generation          | 1749.74 TWh                               |
| Installation costs  | 665 €/kW <sub>p</sub> / 562.590 billion € |
| Lifetime            | 25 years                                  |
| Excess generation   | 158.93 TWh                                |
| Revenues            | -3.973 billion € p.a. (0.025 €/kWh)       |
| O&M costs           | 11.252 billion € p.a.                     |
| <b>Transmission</b> |                                           |
| Costs               | 81.021 billion €                          |
| Lifetime            | 25 years                                  |
| O&M costs           | 0.810 billion € p.a.                      |
| Losses              | 1.5% + 14.2%                              |
| <b>Storage</b>      | <b>pumped hydro</b>                       |
| Capacity            | 567.18 GW / 3,500 GWh                     |
| Efficiency          | 85%                                       |
| Installation costs  | 674 €/kW / 382.308 billion €              |
| Lifetime            | 40 years                                  |
| O&M costs           | 3.399 billion € p.a.                      |

Table 159. Cost calculations (150 GW base load with PV)

|                                    |             |
|------------------------------------|-------------|
| <b>Resulting LEC</b>               |             |
| Interest rate 6%                   | 0.066 €/kWh |
| Interest rate 8%                   | 0.079 €/kWh |
| <b>LEC Breakdown<br/>for IR=6%</b> |             |
| PV generation                      | 44.1%       |
| Transmission                       | 15.1%       |
| Storage and dumping                | 40.7%       |

### 8.2.2.5.2 Scenario B (Solar Thermal Power) - 150 GW in 2020/2030

Table 160. Estimates for Supply Zones and Power Transmission

| Zone         | Reference<br>and<br>Transmission<br>Distance<br>in km | Transm.<br>Losses | Transm.<br>Capacity<br>in GW | Supply<br>Power<br>in GW | New 5 GW<br>lines and<br>HVDC stations |
|--------------|-------------------------------------------------------|-------------------|------------------------------|--------------------------|----------------------------------------|
| A3-E         | 5,100                                                 | 13.8%             | 19.5                         | 16.8                     | 15,300 / 3.0                           |
| A3-G1        | 3,800                                                 | 10.0%             | 182.0                        | 163.8                    | 106,400 / 14.0                         |
| G1-G         | 0                                                     | 0.5%              | 6.5                          | 6.5                      | 0 / 0.5                                |
| G1-B         | 2,100                                                 | 5.8%              | 13.0                         | 12.3                     | 4,200 / 1.0                            |
| G1-D         | 1,700                                                 | 4.8%              | 32.5                         | 31.0                     | 8,500 / 2.5                            |
| G1-F         | 1,800                                                 | 5.0%              | 32.5                         | 30.9                     | 9,000 / 2.5                            |
| G1-I         | 800                                                   | 2.5%              | 19.5                         | 19.0                     | 2,400 / 1.5                            |
| G1-P         | 1,000                                                 | 3.0%              | 26.0                         | 25.2                     | 4,000 / 2.0                            |
| G1-S         | 1,400                                                 | 4.0%              | 6.5                          | 6.2                      | 1,400 / 0.5                            |
| G1-U         | 2,700                                                 | 7.3%              | 26.0                         | 24.1                     | 10,800 / 2.0                           |
| <b>Total</b> | <b>5,220</b>                                          | <b>14.1%</b>      | <b>200.0</b>                 | <b>~170.0</b>            | <b>162,000 / 30</b>                    |

Table 161. Technical Results and assumption for cost calculations (150 GW base load with ST)

|                       |                                     |
|-----------------------|-------------------------------------|
| <b>Base load</b>      | <b>150.0 GW</b><br><b>1,314 TWh</b> |
| <b>ST Power</b>       |                                     |
| Capacity              | 208 GW <sub>el</sub>                |
| Field Size            | 4,684.2 million m <sup>2</sup>      |
| Collector orientation | E-W                                 |
| Thermal Storage       | 12,193 GWh <sub>th</sub>            |
| Generation            | 1,661.8 TWh                         |
| Installation costs    | 2,608 €/kW <sub>el</sub>            |
|                       | 542.455 billion €                   |
| Lifetime              | 25 years                            |
| O&M costs             | 15.731 billion € p.a.               |
| <b>Transmission</b>   |                                     |
| Costs                 | 59.130 billion €                    |
| Lifetime              | 25 years                            |
| O&M costs             | 0.591 billion € p.a.                |
| Losses                | 14.1%                               |
| <b>Storage</b>        | pumped hydro                        |
| Capacity              | 47.6 GW / 375 GWh                   |
| Efficiency            | 85%                                 |
| Installation costs    | 695 €/kW / 33.060 billion €         |
| Lifetime              | 40 years                            |
| O&M costs             | 0.073 billion € p.a.                |

Table 162. Cost calculations (150 GW base load with ST)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.050 €/kWh |
| Interest rate 8%               | 0.057 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| ST generation                  | 70.1%       |
| Transmission                   | 17.6%       |
| Storage and dumping            | 12.3%       |

## 8.2.3 Remaining Load Scenarios for Today

### 8.2.3.1 5 GW Remaining Load today

#### 8.2.3.1.1 Scenario A (Photovoltaic) - 5 GW today

Table 163. Estimates for Power Transmission

| Type | Supply Power in GW | New HV Transmission Lines in km | Transmission Losses | Investment Costs in billion € |
|------|--------------------|---------------------------------|---------------------|-------------------------------|
| AC   | 32.9               | 350                             | 1.5%                | 2.285 billion €               |
| DC   | 11.2               | 14,600 / 3                      | 18.0%               | 6.337 billion €               |

Table 164. Technical Results and assumption for cost calculations (5 GW remaining load with PV)

|                             |                                            |
|-----------------------------|--------------------------------------------|
| <b>Remaining load</b>       |                                            |
| Average                     | 5.0 GW<br>43.8 TWh                         |
| Maximum                     | 9.5 GW                                     |
| Minimum                     | 0 GW                                       |
| <b>Photovoltaic</b>         |                                            |
| Capacity                    | 39 GW <sub>p</sub>                         |
| Generation                  | 80.97 TWh                                  |
| Installation costs          | 1,971 €/kW <sub>p</sub> / 76.869 billion € |
| Lifetime                    | 25 years                                   |
| Excess generation           | 19.22 TWh                                  |
| Revenues                    | -0.384 billion € p.a. (0.02 €/kWh)         |
| O&M costs                   | 2.075 billion € p.a.                       |
| <b>Transmission</b>         |                                            |
| Costs                       | 8.622 billion €                            |
| Lifetime                    | 25 years                                   |
| O&M costs                   | 0.086 billion € p.a.                       |
| Losses                      | 1.5% + 18.0%                               |
| <b>Storage</b> pumped hydro |                                            |
| Capacity                    | 28.68 GW / 380 GWh                         |
| Efficiency                  | 75%                                        |
| Installation costs          | 885 €/kW / 25.396 billion €                |
| Lifetime                    | 40 years                                   |
| O&M costs                   | 0.162 billion € p.a.                       |

Table 165. Cost calculations (5 GW remaining load with PV)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.235 €/kWh |
| Interest rate 8%               | 0.276 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| PV generation                  | 40.4%       |
| Transmission                   | 15.3%       |
| Storage and dumping            | 44.3%       |



### 8.2.3.1.2 Scenario B (Solar Thermal Power) - 5 GW today

Table 166. Technical Results and assumption for cost calculations (5 GW remaining load with ST)

|                       |                                              |
|-----------------------|----------------------------------------------|
| <b>Remaining load</b> |                                              |
| Average               | 5.0 GW<br>43.8 TWh                           |
| Maximum               | 9.5 GW                                       |
| Minimum               | 0 GW                                         |
| <b>ST Power</b>       |                                              |
| Capacity              | 11.2 GW <sub>el</sub>                        |
| Field Size            | 220.0 million m <sup>2</sup>                 |
| Collector orientation | E-W                                          |
| Thermal Storage       | 435.9 GWh <sub>th</sub>                      |
| Generation for Export | 51.940 TWh                                   |
| Installation costs    | 2,967 €/kW <sub>el</sub><br>33.265 billion € |
| Excess generation     | 29.021 TWh                                   |
| Revenues              | -0.580 billion € p.a. (0.02 €/kWh)           |
| Lifetime              | 25 years                                     |
| O&M costs             | 0.965 billion € p.a.                         |
| <b>Transmission</b>   |                                              |
| Costs                 | 6.377 billion €                              |
| Lifetime              | 25 years                                     |
| O&M costs             | 0.064 billion € p.a.                         |
| Losses                | 18%                                          |
| <b>Storage</b>        | none                                         |

Table 167. Cost calculations (5 GW remaining load with ST)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.081 €/kWh |
| Interest rate 8%               | 0.095 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| ST generation                  | 54.4%       |
| Transmission and dumping       | 45.6%       |

### 8.2.3.2 10 GW Remaining Load today

#### 8.2.3.2.1 Scenario A (Photovoltaic) - 10 GW in 2020/2030

Table 168. Estimates for Power Transmission

| Type | Supply Power in GW | New HV Transmission Lines in km | Transmission Losses | Investment Costs in billion € |
|------|--------------------|---------------------------------|---------------------|-------------------------------|
| AC   | 65.0               | 350                             | 1.5%                | 4.334 billion €               |
| DC   | 22.4               | 29,100 / 5                      | 18.0%               | 11.484 billion €              |

Table 169. Technical Results and assumption for cost calculations (10 GW remaining load with PV)

|                             |                                             |
|-----------------------------|---------------------------------------------|
| <b>Remaining load</b>       |                                             |
| Average                     | 10.0 GW<br>87.6 TWh                         |
| Maximum                     | 18.9 GW                                     |
| Minimum                     | 0 GW                                        |
| <b>Photovoltaic</b>         |                                             |
| Capacity                    | 77 GW <sub>p</sub>                          |
| Generation                  | 159.87 TWh                                  |
| Installation costs          | 1,819 €/kW <sub>p</sub> / 140.063 billion € |
| Lifetime                    | 25 years                                    |
| Excess generation           | 36.48 TWh                                   |
| Revenues                    | -0.730 billion € p.a. (0.02 €/kWh)          |
| O&M costs                   | 3.782 billion € p.a.                        |
| <b>Transmission</b>         |                                             |
| Costs                       | 15.819 billion €                            |
| Lifetime                    | 25 years                                    |
| O&M costs                   | 0.158 billion € p.a.                        |
| Losses                      | 1.5% + 18.0%                                |
| <b>Storage</b> pumped hydro |                                             |
| Capacity                    | 56.55 GW / 890 GWh                          |
| Efficiency                  | 75%                                         |
| Installation costs          | 920 €/kW / 52.045 billion €                 |
| Lifetime                    | 40 years                                    |
| O&M costs                   | 0.323 billion € p.a.                        |

Table 170. Cost calculations (10 GW remaining load with PV)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.219 €/kWh |
| Interest rate 8%               | 0.257 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| PV generation                  | 40.0%       |
| Transmission                   | 15.1%       |
| Storage and dumping            | 44.9%       |

### 8.2.3.2.2 Scenario B (Solar Thermal Power) - 10 GW today

Table 171. Technical Results and assumption for cost calculations (10 GW remaining load with ST)

|                       |                                              |
|-----------------------|----------------------------------------------|
| <b>Remaining load</b> |                                              |
| Average               | 10.0 GW<br>87.6 TWh                          |
| Maximum               | 18.9 GW                                      |
| Minimum               | 0 GW                                         |
| <b>ST Power</b>       |                                              |
| Capacity              | 22.3 GW <sub>el</sub>                        |
| Field Size            | 437.6 million m <sup>2</sup>                 |
| Collector orientation | E-W                                          |
| Thermal Storage       | 867.3 GWh <sub>th</sub>                      |
| Generation for Export | 103.333 TWh                                  |
| Installation costs    | 2,616 €/kW <sub>el</sub><br>58.353 billion € |
| Excess generation     | 57.737 TWh                                   |
| Revenues              | -1.155 billion € p.a. (0.02 €/kWh)           |
| Lifetime              | 25 years                                     |
| O&M costs             | 1.692 billion € p.a.                         |
| <b>Transmission</b>   |                                              |
| Costs                 | 11.484 billion €                             |
| Lifetime              | 25 years                                     |
| O&M costs             | 0.115 billion € p.a.                         |
| Losses                | 18%                                          |
| <b>Storage</b>        | none                                         |

Table 172. Cost calculations (10 GW remaining load with ST)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.070 €/kWh |
| Interest rate 8%               | 0.082 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| ST generation                  | 55.6%       |
| Transmission and dumping       | 44.4%       |

### 8.2.3.3 100 GW Remaining Load today

#### 8.2.3.3.1 Scenario A (Photovoltaic) - 100 GW today

Table 173. Estimates for Power Transmission

| Type | Supply Power in GW | New HV Transmission Lines in km | Transmission Losses | Investment Costs in billion € |
|------|--------------------|---------------------------------|---------------------|-------------------------------|
| AC   | 699.7              | 350                             | 1.5%                | 40.569 billion €              |
| DC   | 223.6              | 290,700 / 52                    | 18.0%               | 101.360 billion €             |

Table 174. Technical Results and assumption for cost calculations (100 GW remaining load with PV)

|                             |                                           |
|-----------------------------|-------------------------------------------|
| <b>Remaining load</b>       |                                           |
| Average                     | 100 GW<br>876 TWh                         |
| Maximum                     | 189.5 GW                                  |
| Minimum                     | 0 GW                                      |
| <b>Photovoltaic</b>         |                                           |
| Capacity                    | 829 GW <sub>p</sub>                       |
| Generation                  | 1,721.17 TWh                              |
| Installation costs          | 1,368 €/kW <sub>p</sub> / 1,134 billion € |
| Lifetime                    | 25 years                                  |
| Excess generation           | 481.75 TWh                                |
| Revenues                    | -9.635 billion € p.a. (0.02 €/kWh)        |
| O&M costs                   | 30.620 billion € p.a.                     |
| <b>Transmission</b>         |                                           |
| Costs                       | 141.929 billion €                         |
| Lifetime                    | 25 years                                  |
| O&M costs                   | 1.419 billion € p.a.                      |
| Losses                      | 1.5% + 19.5%                              |
| <b>Storage</b> pumped hydro |                                           |
| Capacity                    | 613.27 GW / 4,000 GWh                     |
| Efficiency                  | 75%                                       |
| Installation costs          | 791 €/kW / 485.291 billion €              |
| Lifetime                    | 40 years                                  |
| O&M costs                   | 3.222 billion € p.a.                      |

Table 175. Cost calculations (100 GW remaining load with PV)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.180 €/kWh |
| Interest rate 8%               | 0.212 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| PV generation                  | 35.4%       |
| Transmission                   | 14.8%       |
| Storage and dumping            | 49.8%       |

### 8.2.3.3.2 Scenario B (Solar Thermal Power) - 100 GW today

Table 176. Technical Results and assumption for cost calculations (100 GW remaining load with ST)

|                       |                                               |
|-----------------------|-----------------------------------------------|
| <b>Remaining load</b> |                                               |
| Average               | 100 GW<br>876 TWh                             |
| Maximum               | 189.5 GW                                      |
| Minimum               | 0 GW                                          |
| <b>ST Power</b>       |                                               |
| Capacity              | 223.6 GW <sub>el</sub>                        |
| Field Size            | 4387.7 million m <sup>2</sup>                 |
| Collector orientation | E-W                                           |
| Thermal Storage       | 8,695.9 GWh <sub>th</sub>                     |
| Generation for Export | 1,036.0 TWh                                   |
| Installation costs    | 2,246 €/kW <sub>el</sub><br>502.306 billion € |
| Excess generation     | 578.9 TWh                                     |
| Revenues              | -11.58 billion € p.a. (0.02 €/kWh)            |
| Lifetime              | 25 years                                      |
| O&M costs             | 14.567 billion € p.a.                         |
| <b>Transmission</b>   |                                               |
| Costs                 | 101.36 billion €                              |
| Lifetime              | 25 years                                      |
| O&M costs             | 1.014 billion € p.a.                          |
| Losses                | 18%                                           |
| <b>Storage</b>        | none                                          |

Table 177. Cost calculations (100 GW remaining load with ST)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.058 €/kWh |
| Interest rate 8%               | 0.069 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| ST generation                  | 57.0%       |
| Transmission and dumping       | 44.0%       |

### 8.2.3.4 150 GW Remaining Load today

#### 8.2.3.4.1 Scenario A (Photovoltaic) - 150 GW today

Table 178. Estimates for Power Transmission

| Type | Supply Power in GW | New HV Transmission Lines in km | Transmission Losses | Investment Costs in billion € |
|------|--------------------|---------------------------------|---------------------|-------------------------------|
| AC   | 1,049.1            | 350                             | 1.5%                | 59.395 billion €              |
| DC   | 335.4              | 436,000 / 77                    | 18.0%               | 147.881 billion €             |

Table 179. Technical Results and assumption for cost calculations (150 GW remaining load with PV)

|                             |                                           |
|-----------------------------|-------------------------------------------|
| <b>Remaining load</b>       |                                           |
| Average                     | 150 GW<br>1,314 TWh                       |
| Maximum                     | 284.3 GW                                  |
| Minimum                     | 0 GW                                      |
| <b>Photovoltaic</b>         |                                           |
| Capacity                    | 1,243 GW <sub>p</sub>                     |
| Generation                  | 2,580.72 TWh                              |
| Installation costs          | 1,304 €/kW <sub>p</sub> / 1,621 billion € |
| Lifetime                    | 25 years                                  |
| Excess generation           | 721.61 TWh                                |
| Revenues                    | -14.42 billion € p.a. (0.02 €/kWh)        |
| O&M costs                   | 43.764 billion € p.a.                     |
| <b>Transmission</b>         |                                           |
| Costs                       | 207.276 billion €                         |
| Lifetime                    | 25 years                                  |
| O&M costs                   | 2.073 billion € p.a.                      |
| Losses                      | 1.5% + 18.0%                              |
| <b>Storage</b> pumped hydro |                                           |
| Capacity                    | 919.5 GW / 6,000 GWh                      |
| Efficiency                  | 75%                                       |
| Installation costs          | 791 €/kW / 727.653 billion €              |
| Lifetime                    | 40 years                                  |
| O&M costs                   | 4.832 billion € p.a.                      |



Table 180. Cost calculations (150 GW remaining load with PV)

|                                    |             |
|------------------------------------|-------------|
| <b>Resulting LEC</b>               |             |
| Interest rate 6%                   | 0.173 €/kWh |
| Interest rate 8%                   | 0.204 €/kWh |
| <b>LEC Breakdown<br/>for IR=6%</b> |             |
| PV generation                      | 34.9%       |
| Transmission                       | 14.8%       |
| Storage and dumping                | 50.2%       |

### 8.2.3.4.2 Scenario B (Solar Thermal Power) - 150 GW today

Table 181. Technical Results and assumption for cost calculations (150 GW remaining load with ST)

|                       |                                             |
|-----------------------|---------------------------------------------|
| <b>Remaining load</b> |                                             |
| Average               | 150 GW<br>1,314 TWh                         |
| Maximum               | 284.3 GW                                    |
| Minimum               | 0 GW                                        |
| <b>ST Power</b>       |                                             |
| Capacity              | 335.5 GW <sub>el</sub>                      |
| Field Size            | 6,582.7 million m <sup>2</sup>              |
| Collector orientation | E-W                                         |
| Thermal Storage       | 13,046.2 GWh <sub>th</sub>                  |
| Generation for Export | 1,554.4 TWh                                 |
| Installation costs    | 2,195 €/kW <sub>el</sub><br>736.5 billion € |
| Excess generation     | 868.5 TWh                                   |
| Revenues              | -17.37 billion € p.a. (0.02 €/kWh)          |
| Lifetime              | 25 years                                    |
| O&M costs             | 21.357 billion € p.a.                       |
| <b>Transmission</b>   |                                             |
| Costs                 | 147.88 billion €                            |
| Lifetime              | 25 years                                    |
| O&M costs             | 1.479 billion € p.a.                        |
| Losses                | 18%                                         |
| <b>Storage</b>        |                                             |
|                       | none                                        |

Table 182 Cost calculations (150 GW remaining load with ST)

|                                    |             |
|------------------------------------|-------------|
| <b>Resulting LEC</b>               |             |
| Interest rate 6%                   | 0.057 €/kWh |
| Interest rate 8%                   | 0.067 €/kWh |
| <b>LEC Breakdown<br/>for IR=6%</b> |             |
| ST generation                      | 57.4%       |
| Transmission and dumping           | 42.6%       |

## 8.2.4 Remaining Load Scenarios for 2020/2030

### 8.2.4.1 5 GW Remaining Load in 2020/2030

#### 8.2.4.1.1 Scenario A (Photovoltaic) - 5 GW in 2020/2030

Table 183. Estimates for Power Transmission

| Type | Supply Power in GW | New HV Transmission Lines in km | Transmission Losses | Investment Costs in billion € |
|------|--------------------|---------------------------------|---------------------|-------------------------------|
| AC   | 27.9               | 350                             | 1.5%                | 1.367 billion €               |
| DC   | 10.8               | 20,000 / 2                      | 14.0%               | 4.400 billion €               |

Table 184. Technical Results and assumption for cost calculations (5 GW remaining load with PV)

|                             |                                            |
|-----------------------------|--------------------------------------------|
| <b>Remaining load</b>       |                                            |
| Average                     | 5.0 GW<br>43.8 TWh                         |
| Maximum                     | 9.5 GW                                     |
| Minimum                     | 0 GW                                       |
| <b>Photovoltaic</b>         |                                            |
| Capacity                    | 33 GW <sub>p</sub>                         |
| Generation                  | 68.51 TWh                                  |
| Installation costs          | 1,107 €/kW <sub>p</sub> / 36.531 billion € |
| Lifetime                    | 25 years                                   |
| Excess generation           | 16.44 TWh                                  |
| Revenues                    | -0.411 billion € p.a. (0.025 €/kWh)        |
| O&M costs                   | 0.731 billion € p.a.                       |
| <b>Transmission</b>         |                                            |
| Costs                       | 5.767 billion €                            |
| Lifetime                    | 25 years                                   |
| O&M costs                   | 0.058 billion € p.a.                       |
| Losses                      | 1.5% + 14.0%                               |
| <b>Storage</b> pumped hydro |                                            |
| Capacity                    | 25.26 GW / 410 GWh                         |
| Efficiency                  | 85%                                        |
| Installation costs          | 795 €/kW / 20.074 billion €                |
| Lifetime                    | 40 years                                   |
| O&M costs                   | 0.105 billion € p.a.                       |

Table 185. Cost calculations (5 GW remaining load with PV)

|                                    |             |
|------------------------------------|-------------|
| <b>Resulting LEC</b>               |             |
| Interest rate 6%                   | 0.117 €/kWh |
| Interest rate 8%                   | 0.140 €/kWh |
| <b>LEC Breakdown<br/>for IR=6%</b> |             |
| PV generation                      | 39.6%       |
| Transmission                       | 16.1%       |
| Storage and dumping                | 44.3%       |

### 8.2.4.1.2 Scenario B (Solar Thermal Power) - 5 GW in 2020/2030

Table 186. Technical Results and assumption for cost calculations (5 GW remaining load with ST)

|                       |                                              |
|-----------------------|----------------------------------------------|
| <b>Remaining load</b> |                                              |
| Average               | 5.0 GW<br>43.8 TWh                           |
| Maximum               | 9.5 GW                                       |
| Minimum               | 0 GW                                         |
| <b>ST Power</b>       |                                              |
| Capacity              | 10.83 GW <sub>el</sub>                       |
| Field Size            | 201.9 million m <sup>2</sup>                 |
| Collector orientation | E-W                                          |
| Thermal Storage       | 400.11 GWh <sub>th</sub>                     |
| Generation for Export | 50.179 TWh                                   |
| Installation costs    | 2,545 €/kW <sub>el</sub><br>27.560 billion € |
| Excess generation     | 28.038 TWh                                   |
| Revenues              | -0.70 billion € p.a. (0.025 €/kWh)           |
| Lifetime              | 25 years                                     |
| O&M costs             | 0.799 billion € p.a.                         |
| <b>Transmission</b>   |                                              |
| Costs                 | 4.4 billion €                                |
| Lifetime              | 25 years                                     |
| O&M costs             | 0.044 billion € p.a.                         |
| Losses                | 14%                                          |
| <b>Storage</b>        |                                              |
|                       | none                                         |

Table 187. Cost calculations (5 GW remaining load with ST)

|                                    |             |
|------------------------------------|-------------|
| <b>Resulting LEC</b>               |             |
| Interest rate 6%                   | 0.060 €/kWh |
| Interest rate 8%                   | 0.072 €/kWh |
| <b>LEC Breakdown<br/>for IR=6%</b> |             |
| ST generation                      | 62.5%       |
| Transmission and dumping           | 37.5%       |

## 8.2.4.2 10 GW Remaining Load in 2020/2030

### 8.2.4.2.1 Scenario A (Photovoltaic) - 10 GW in 2020/2030

Table 188. Estimates for Power Transmission

| Type | Supply Power in GW | New HV Transmission Lines in km | Transmission Losses | Investment Costs in billion € |
|------|--------------------|---------------------------------|---------------------|-------------------------------|
| AC   | 56.6               | 350                             | 1.5%                | 2.662 billion €               |
| DC   | 21.6               | 20,500 / 4                      | 14.0%               | 8.580 billion €               |

Table 189. Technical Results and assumption for cost calculations (10 GW remaining load with PV)

|                             |                                          |
|-----------------------------|------------------------------------------|
| <b>Remaining load</b>       |                                          |
| Average                     | 10.0 GW<br>87.6 TWh                      |
| Maximum                     | 18.9 GW                                  |
| Minimum                     | 0 GW                                     |
| <b>Photovoltaic</b>         |                                          |
| Capacity                    | 67 GW <sub>p</sub>                       |
| Generation                  | 139.11 TWh                               |
| Installation costs          | 990 €/kW <sub>p</sub> / 66.330 billion € |
| Lifetime                    | 25 years                                 |
| Excess generation           | 34.94 TWh                                |
| Revenues                    | -0.873 billion € p.a. (0.025 €/kWh)      |
| O&M costs                   | 1.327 billion € p.a.                     |
| <b>Transmission</b>         |                                          |
| Costs                       | 11.241 billion €                         |
| Lifetime                    | 25 years                                 |
| O&M costs                   | 0.112 billion € p.a.                     |
| Losses                      | 1.5% + 14.0%                             |
| <b>Storage</b> pumped hydro |                                          |
| Capacity                    | 51.36 GW / 665 GWh                       |
| Efficiency                  | 85%                                      |
| Installation costs          | 755 €/kW / 38.797 billion €              |
| Lifetime                    | 40 years                                 |
| O&M costs                   | 0.209 billion € p.a.                     |



Table 190. Cost calculations (10 GW remaining load with PV)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.108 €/kWh |
| Interest rate 8%               | 0.129 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| PV generation                  | 37.7%       |
| Transmission                   | 16.4%       |
| Storage and dumping            | 45.9%       |

#### 8.2.4.2.2 Scenario B (Solar Thermal Power) - 10 GW in 2020/2030

Table 191. Technical Results and assumption for cost calculations (10 GW remaining load with ST)

|                       |                                              |
|-----------------------|----------------------------------------------|
| <b>Remaining load</b> |                                              |
| Average               | 10.0 GW<br>87.6 TWh                          |
| Maximum               | 18.9 GW                                      |
| Minimum               | 0 GW                                         |
| <b>ST Power</b>       |                                              |
| Capacity              | 21.55 GW <sub>el</sub>                       |
| Field Size            | 401.6 million m <sup>2</sup>                 |
| Collector orientation | E-W                                          |
| Thermal Storage       | 796.01 GWh <sub>th</sub>                     |
| Generation for Export | 99.830 TWh                                   |
| Installation costs    | 2,398 €/kW <sub>el</sub><br>55.780 billion € |
| Excess generation     | 28.038 TWh                                   |
| Revenues              | -1.40 billion € p.a. (0.025 €/kWh)           |
| Lifetime              | 25 years                                     |
| O&M costs             | 1.499 billion € p.a.                         |
| <b>Transmission</b>   |                                              |
| Costs                 | 8.58 billion €                               |
| Lifetime              | 25 years                                     |
| O&M costs             | 0.086 billion € p.a.                         |
| Losses                | 14%                                          |
| <b>Storage</b>        | none                                         |

Table 192. Cost calculations (10 GW remaining load with ST)

|                                    |             |
|------------------------------------|-------------|
| <b>Resulting LEC</b>               |             |
| Interest rate 6%                   | 0.056 €/kWh |
| Interest rate 8%                   | 0.067 €/kWh |
| <b>LEC Breakdown<br/>for IR=6%</b> |             |
| ST generation                      | 63.5%       |
| Transmission and dumping           | 36.5%       |

### 8.2.4.3 100 GW Remaining Load in 2020/2030

#### 8.2.4.3.1 Scenario A (Photovoltaic) - 100 GW in 2020/2030

Table 193. Estimates for Power Transmission

| Type | Supply Power in GW | New HV Transmission Lines in km | Transmission Losses | Investment Costs in billion € |
|------|--------------------|---------------------------------|---------------------|-------------------------------|
| AC   | 594.2              | 350                             | 1.5%                | 24.350 billion €              |
| DC   | 216.0              | 205,200 / 37                    | 14.0%               | 73.203 billion €              |

Table 194. Technical Results and assumption for cost calculations (100 GW remaining load with PV)

|                             |                                           |
|-----------------------------|-------------------------------------------|
| <b>Remaining load</b>       |                                           |
| Average                     | 100 GW<br>876 TWh                         |
| Maximum                     | 189.5 GW                                  |
| Minimum                     | 0 GW                                      |
| <b>Photovoltaic</b>         |                                           |
| Capacity                    | 704 GW <sub>p</sub>                       |
| Generation                  | 1,461.65 TWh                              |
| Installation costs          | 679 €/kW <sub>p</sub> / 478.016 billion € |
| Lifetime                    | 25 years                                  |
| Excess generation           | 420.27 TWh                                |
| Revenues                    | -10.51 billion € p.a. (0.025 €/kWh)       |
| O&M costs                   | 9.560 billion € p.a.                      |
| <b>Transmission</b>         |                                           |
| Costs                       | 97.553 billion €                          |
| Lifetime                    | 25 years                                  |
| O&M costs                   | 0.976 billion € p.a.                      |
| Losses                      | 1.5% + 14.0%                              |
| <b>Storage</b> pumped hydro |                                           |
| Capacity                    | 542.53 GW / 4,000 GWh                     |
| Efficiency                  | 85%                                       |
| Installation costs          | 688 €/kW / 373.517 billion €              |
| Lifetime                    | 40 years                                  |
| O&M costs                   | 2.084 billion € p.a.                      |

Table 195. Cost calculations (100 GW remaining load with PV)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.082 €/kWh |
| Interest rate 8%               | 0.100 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| PV generation                  | 30.4%       |
| Transmission                   | 16.7%       |
| Storage and dumping            | 53.0%       |

### 8.2.4.3.2 Scenario B (Solar Thermal Power) - 100 GW in 2020/2030

Table 196. Technical Results and assumption for cost calculations (100 GW remaining load with ST)

|                       |                                              |
|-----------------------|----------------------------------------------|
| <b>Remaining load</b> |                                              |
| Average               | 100 GW<br>876 TWh                            |
| Maximum               | 189.5 GW                                     |
| Minimum               | 0 GW                                         |
| <b>ST Power</b>       |                                              |
| Capacity              | 216.03 GW <sub>el</sub>                      |
| Field Size            | 4,027 million m <sup>2</sup>                 |
| Collector orientation | E-W                                          |
| Thermal Storage       | 7,981 GWh <sub>th</sub>                      |
| Generation for Export | 1,000.9 TWh                                  |
| Installation costs    | 2,105 €/kW <sub>el</sub><br>454.83 billion € |
| Excess generation     | 559.28 TWh                                   |
| Revenues              | -14.0 billion € p.a. (0.025 €/kWh)           |
| Lifetime              | 25 years                                     |
| O&M costs             | 13.190 billion € p.a.                        |
| <b>Transmission</b>   |                                              |
| Costs                 | 73.203 billion €                             |
| Lifetime              | 25 years                                     |
| O&M costs             | 0.732 billion € p.a.                         |
| Losses                | 14%                                          |
| <b>Storage</b>        | none                                         |

Table 197. Cost calculations (100 GW remaining load with ST).

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.047 €/kWh |
| Interest rate 8%               | 0.057 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| ST generation                  | 66.2%       |
| Transmission and dumping       | 33.8%       |

## 8.2.4.4 150 GW Remaining Load in 2020/2030

### 8.2.4.4.1 Scenario A (Photovoltaic) - 150 GW in 2020/2030

Table 198. Estimates for Power Transmission

| Type | Supply Power in GW | New HV Transmission Lines in km | Transmission Losses | Investment Costs in billion € |
|------|--------------------|---------------------------------|---------------------|-------------------------------|
| AC   | 891.3              | 350                             | 1.5%                | 35.662 billion €              |
| DC   | 324.0              | 307,800 / 55                    | 14.0%               | 106.928 billion €             |

Table 199. Technical Results and assumption for cost calculations (150 GW remaining load with PV)

|                             |                                           |
|-----------------------------|-------------------------------------------|
| <b>Remaining load</b>       |                                           |
| Average                     | 150 GW<br>1,314 TWh                       |
| Maximum                     | 284.3 GW                                  |
| Minimum                     | 0 GW                                      |
| <b>Photovoltaic</b>         |                                           |
| Capacity                    | 1,056 GW <sub>p</sub>                     |
| Generation                  | 2,192.47 TWh                              |
| Installation costs          | 649 €/kW <sub>p</sub> / 685.344 billion € |
| Lifetime                    | 25 years                                  |
| Excess generation           | 630.40 TWh                                |
| Revenues                    | -15.76 billion € p.a. (0.025 €/kWh)       |
| O&M costs                   | 13.707 billion € p.a.                     |
| <b>Transmission</b>         |                                           |
| Costs                       | 142.590 billion €                         |
| Lifetime                    | 25 years                                  |
| O&M costs                   | 1.426 billion € p.a.                      |
| Losses                      | 1.5% + 14.0%                              |
| <b>Storage</b> pumped hydro |                                           |
| Capacity                    | 813.79 GW / 6,000 GWh                     |
| Efficiency                  | 85%                                       |
| Installation costs          | 688 €/kW / 560.276 billion €              |
| Lifetime                    | 40 years                                  |
| O&M costs                   | 3.126 billion € p.a.                      |

Table 200. Cost calculations (150 GW remaining load with PV)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.080 €/kWh |
| Interest rate 8%               | 0.097 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| PV generation                  | 29.6%       |
| Transmission                   | 16.6%       |
| Storage and dumping            | 53.8%       |



#### 8.2.4.4.2 Scenario B (Solar Thermal Power) - 150 GW in 2020/2030

Table 201. Technical Results and assumption for cost calculations (150 GW remaining load with ST)

|                       |                                               |
|-----------------------|-----------------------------------------------|
| <b>Remaining load</b> |                                               |
| Average               | 150 GW<br>1,314 TWh                           |
| Maximum               | 284.3 GW                                      |
| Minimum               | 0 GW                                          |
| <b>ST Power</b>       |                                               |
| Capacity              | 324.1 GW <sub>el</sub>                        |
| Field Size            | 6,041.6 million m <sup>2</sup>                |
| Collector orientation | E-W                                           |
| Thermal Storage       | 11,973.8 GWh <sub>th</sub>                    |
| Generation for Export | 1,501.7 TWh                                   |
| Installation costs    | 2,057 €/kW <sub>el</sub><br>666,539 billion € |
| Excess generation     | 839.06 TWh                                    |
| Revenues              | -21.0 billion € p.a. (0.025 €/kWh)            |
| Lifetime              | 25 years                                      |
| O&M costs             | 19.330 billion € p.a.                         |
| <b>Transmission</b>   |                                               |
| Costs                 | 106.93 billion €                              |
| Lifetime              | 25 years                                      |
| O&M costs             | 1.069 billion € p.a.                          |
| Losses                | 14%                                           |
| <b>Storage</b>        |                                               |
|                       | none                                          |

Table 202. Cost calculations (150 GW remaining load with ST)

|                                |             |
|--------------------------------|-------------|
| <b>Resulting LEC</b>           |             |
| Interest rate 6%               | 0.046 €/kWh |
| Interest rate 8%               | 0.055 €/kWh |
| <b>LEC Breakdown for IR=6%</b> |             |
| ST generation                  | 66.8%       |
| Transmission and dumping       | 33.2%       |

### 8.2.5 Combined space-terrestrial scenarios

For all combined scenarios the demand load curve is the same, their key values are listed in Table 75 and Table 203. Table 204 shows the corresponding estimates for the DC power transmission lines, which are necessary for supplying the named demand in Europe.

Table 203. Key values of the demand load curve of all combined space-terrestrial scenarios

| Minimum load / GW | Average load / GW | Maximum load / GW | Demand sum / TWh |
|-------------------|-------------------|-------------------|------------------|
| 266               | 439               | 593               | 3843             |

Table 204. Estimates for DC power transmission for the combined systems

| Type | Supply Power in GW | New HV Transmission Lines in km | Transmission Losses | Investment Costs in billion € |
|------|--------------------|---------------------------------|---------------------|-------------------------------|
| DC   | 676.0              | 642,188 / 115                   | 14.0%               | 213.772 billion €             |

Lifetime of SPS: 30 years, PV on ground: 25 years; storage: 40 years, transmission lines: 25 years.

### 8.2.5.1 Scenario 1

Table 205. Technical results and assumptions for cost calculation for scenario 1 at transport costs of 530 €/kg

| SPS system                   |                   | Terrestrial only |        | ...    | combined | ...    | SPS only |
|------------------------------|-------------------|------------------|--------|--------|----------|--------|----------|
| Number of SPS                |                   | 0                | 15     | 30     | 45       | 60     | 77       |
| Space PV capacity            | GW <sub>p</sub>   | 0                | 332    | 664    | 996      | 1328   | 1705     |
| Ground power out             | GW <sub>p</sub>   | 0                | 118    | 236    | 353      | 471    | 605      |
| Generation sum               | TWh               | 0                | 941    | 1882   | 2823     | 3764   | 4832     |
| Generation percentage        |                   | 0                | 17.0%  | 34.7%  | 52.9%    | 71.9%  | 92.3%    |
| Spec. installation costs     | €/kW <sub>p</sub> | 0                | 8641   | 7612   | 7166     | 6866   | 6616     |
| Installation costs           | billion €         | 0                | 1018   | 1794   | 2533     | 3236   | 4002     |
| O&M costs                    | billion € p.a.    | 0                | 6.11   | 10.76  | 15.20    | 19.41  | 24.01    |
| Excess selling               | billion € p.a.    | 0                | -3.12  | -6.28  | -9.51    | -12.66 | -17.41   |
| Annual balance               | billion € p.a.    | 0                | 2.98   | 4.48   | 5.69     | 6.75   | 6.60     |
| <b>SPS PV Reciever</b>       |                   |                  |        |        |          |        |          |
| Installed capacity           | GW <sub>p</sub>   | 0                | 42     | 85     | 127      | 170    | 221      |
| Generation sum               | TWh               | 0                | 78     | 155    | 233      | 310    | 403      |
| Generation percentage        |                   | 0                | 1.4%   | 2.9%   | 4.4%     | 5.9%   | 7.7%     |
| Spec. installation costs     | €/kW <sub>p</sub> | 0                | 587    | 604    | 629      | 666    | 754      |
| Installation costs           | billion €         | 0                | 25     | 51     | 80       | 113    | 166      |
| O&M Costs                    | billion € p.a.    | 0                | 0.37   | 0.77   | 1.20     | 1.70   | 2.49     |
| Excess selling               | billion € p.a.    | 0                | -0.26  | -0.52  | -0.78    | -1.04  | -1.45    |
| Annual balance               | billion € p.a.    | 0                | 0.12   | 0.25   | 0.42     | 0.65   | 1.04     |
| <b>Terrestrial PV</b>        |                   |                  |        |        |          |        |          |
| Installed capacity           | GW <sub>p</sub>   | 2621             | 2069   | 1556   | 1045     | 533    | 0        |
| Generation sum               | TWh               | 5714             | 4510   | 3391   | 2278     | 1163   | 0        |
| Generation percentage        |                   | 100%             | 81.6%  | 62.5%  | 42.7%    | 22.2%  | 0%       |
| Spec. installation costs     | €/kW <sub>p</sub> | 584              | 599    | 617    | 641      | 680    | 0        |
| Installation costs           | billion €         | 1530             | 1238   | 959    | 670      | 362    | 0        |
| O&M Costs                    | billion € p.a.    | 30.59            | 24.77  | 19.18  | 13.40    | 7.25   | 0        |
| Excess selling               | billion € p.a.    | -20.62           | -14.97 | -11.32 | -7.67    | -3.91  | 0        |
| Annual balance               | billion € p.a.    | 9.97             | 9.80   | 7.87   | 5.73     | 3.34   | 0        |
| <b>Storage: pumped hydro</b> |                   |                  |        |        |          |        |          |
| Max. power capacity          | GW                | 1828             | 1499   | 1203   | 909      | 614    | 366      |
| Energy capacity              | GWh               | 12476            | 12166  | 11096  | 10055    | 9025   | 7309     |
| Spec. installation costs     | €/kW              | 682              | 697    | 711    | 733      | 776    | 839      |
| Installation Costs           | billion €         | 1247             | 1045   | 855    | 666      | 477    | 308      |
| O&M Costs                    | billion € p.a.    | 9.58             | 7.52   | 5.46   | 3.42     | 1.57   | 0.40     |
| <b>Excess Generation</b>     |                   |                  |        |        |          |        |          |
| Excess generation            | TWh               | 825              | 734    | 725    | 719      | 705    | 755      |
| Revenues                     | billion € p.a.    | -20.6            | -18.4  | -18.1  | -18.0    | -17.6  | -18.9    |
| <b>Transmission lines</b>    |                   |                  |        |        |          |        |          |
| Transmission costs           | billion €         | 302              | 289    | 278    | 267      | 255    | 244      |
| AC transmission costs        | billion €         | 88               | 75     | 64     | 53       | 41     | 30       |
| O&M costs                    | billion € p.a.    | 3.02             | 2.89   | 2.78   | 2.67     | 2.55   | 2.44     |

Table 206. Technical results and assumptions for cost calculation for scenario 1 at transport costs of 2650 €/kg

| SPS system               |                   | Terrestrial only |       | ... | combined | ...   | SPS only           |       |
|--------------------------|-------------------|------------------|-------|-----|----------|-------|--------------------|-------|
| Number of SPS            |                   | 0                | 15    |     | 30       | 45    | 60                 | 77    |
| Space PV capacity        | GW <sub>p</sub>   | 0                | 332   |     | 664      | 996   | 1328               | 1705  |
| Ground power out         | GW <sub>p</sub>   | 0                | 118   |     | 236      | 353   | 471                | 605   |
| Generation sum           | TWh               | 0                | 941   |     | 1882     | 2823  | 3764               | 4832  |
| Generation percentage    |                   | 0                | 17.0% |     | 34.7%    | 53.0% | 71.9%              | 92.3% |
| Spec. installation costs | €/kW <sub>p</sub> | 0                | 28550 |     | 25530    | 24013 | 22992              | 22143 |
| Installation costs       | billion €         | 0                | 3364  |     | 6016     | 8488  | 10836              | 13392 |
| O&M costs                | billion € p.a.    | 0                | 20.2  |     | 36.1     | 50.9  | 65.0               | 80.4  |
| Excess selling           | billion € p.a.    | 0                | -3.1  |     | -6.3     | -9.5  | -12.7              | -17.4 |
| Annual balance           | billion € p.a.    | 0                | 17.1  |     | 29.8     | 41.4  | 52.4               | 62.9  |
| SPS PV Reciever          |                   |                  |       |     |          |       |                    |       |
| Installed capacity       | GW <sub>p</sub>   | 0                | 42    |     | 85       | 127   | 170                | 221   |
| Generation sum           | TWh               | 0                | 78    |     | 155      | 233   | 310                | 403   |
| Generation percentage    |                   | 0                | 1.4%  |     | 2.9%     | 4.4%  | 5.9%               | 7.7%  |
| Spec. installation costs | €/kW <sub>p</sub> | 0                | 587   |     | 604      | 629   | 666                | 754   |
| Installation costs       | billion €         | 0                | 25    |     | 51       | 80    | 113                | 166   |
| O&M Costs                | billion € p.a.    | 0                | 0.37  |     | 0.77     | 1.20  | 1.70               | 2.49  |
| Excess selling           | billion € p.a.    | 0                | -0.26 |     | -0.52    | -0.78 | -1.04              | -1.45 |
| Annual balance           | billion € p.a.    | 0                | 0.12  |     | 0.25     | 0.42  | 0.65               | 1.04  |
| Terrestrial PV           |                   |                  |       |     |          |       |                    |       |
| Installed capacity       | GW <sub>p</sub>   | 2621             | 2069  |     | 1556     | 1044  | 533                | 0     |
| Generation sum           | TWh               | 5714             | 4510  |     | 3391     | 2276  | 1163               | 0     |
| Generation percentage    |                   | 100%             | 81.6% |     | 62.5%    | 42.7% | 22.2%              | 0%    |
| Spec. installation costs | €/kW <sub>p</sub> | 584              | 599   |     | 617      | 641   | 680                | 0     |
| Installation costs       | billion €         | 1530             | 1238  |     | 959      | 669   | 362                | 0     |
| O&M Costs                | billion € p.a.    | 30.6             | 24.8  |     | 19.2     | 13.4  | 7.2                | 0     |
| Excess selling           | billion € p.a.    | -20.6            | -15.0 |     | -11.3    | -7.6  | -3.9               | 0     |
| Annual balance           | billion € p.a.    | 10.0             | 9.8   |     | 7.9      | 5.7   | 3.3                | 0     |
| Storage: pumped hydro    |                   |                  |       |     |          |       |                    |       |
| Max. power capacity      | GW                | 1828             | 1499  |     | 1203     | 908   | 614                | 366   |
| Energy capacity          | GWh               | 12475            | 12166 |     | 11096    | 10054 | 9025               | 7309  |
| Spec. installation costs | €/kW              | 682              | 697   |     | 711      | 733   | 776                | 839   |
| Installation Costs       | billion €         | 1247             | 1045  |     | 855      | 665   | 477                | 308   |
| O&M Costs                | billion € p.a.    | 9.58             | 7.52  |     | 5.46     | 3.42  | 1.57               | 0.40  |
| Excess Generation        |                   |                  |       |     |          |       |                    |       |
| Excess generation        | TWh               | 825              | 734   |     | 725      | 717   | 705                | 755   |
| Revenues                 | billion € p.a.    | -20.6            | -18.4 |     | -18.1    | -17.9 | -17.6              | -18.9 |
| Transmission lines       |                   |                  |       |     |          |       |                    |       |
| Transmission costs       | billion €         | 302              | 289   |     | 278      | 267   | 255                | 244   |
| AC transmission costs    | billion €         | 88               | 75    |     | 64       | 53    | 41                 | 30    |
| O&M costs                | billion € p.a.    | 3.0              | 2.9   |     | 2.8      | 2.7   | 2.6 <sup>2,4</sup> |       |

Table 207. Technical results and assumptions for cost calculation for scenario 1 at transport costs of 5300 €/kg.

| SPS system                   |                   | Terrestrial only |       | ...   | combined | ...   | SPS only |
|------------------------------|-------------------|------------------|-------|-------|----------|-------|----------|
| Number of SPS                |                   | 0                | 15    | 30    | 45       | 60    | 76       |
| Space PV capacity            | GW <sub>p</sub>   | 0                | 332   | 664   | 996      | 1328  | 1683     |
| Ground power out             | GW <sub>p</sub>   | 0                | 118   | 236   | 353      | 471   | 597      |
| Generation sum               | TWh               | 0                | 941   | 1882  | 2823     | 3764  | 4771     |
| Generation percentage        |                   | 0                | 17.0% | 34.7% | 53.0%    | 71.9% | 92.2%    |
| Spec. installation costs     | €/kW <sub>p</sub> | 0                | 53437 | 47928 | 45071    | 43150 | 41632    |
| Installation costs           | billion €         | 0                | 6296  | 11294 | 15931    | 20336 | 24853    |
| O&M costs                    | billion € p.a.    | 0                | 37.8  | 67.8  | 95.6     | 122.0 | 149.1    |
| Excess selling               | billion € p.a.    | 0                | -3.1  | -6.3  | -9.5     | -12.7 | -15.9    |
| Annual balance               | billion € p.a.    | 0                | 34.7  | 61.5  | 86.1     | 109.4 | 133.2    |
| <b>SPS PV Reciever</b>       |                   |                  |       |       |          |       |          |
| Installed capacity           | GW <sub>p</sub>   | 0                | 42    | 85    | 127      | 170   | 221      |
| Generation sum               | TWh               | 0                | 78    | 155   | 233      | 310   | 404      |
| Generation percentage        |                   | 0                | 1.4%  | 2.9%  | 4.4%     | 5.9%  | 7.8%     |
| Spec. installation costs     | €/kW <sub>p</sub> | 0                | 587   | 604   | 629      | 666   | 754      |
| Installation costs           | billion €         | 0                | 25    | 51    | 80       | 113   | 166      |
| O&M Costs                    | billion € p.a.    | 0                | 0.37  | 0.77  | 1.20     | 1.70  | 2.49     |
| Excess selling               | billion € p.a.    | 0                | -0.26 | -0.52 | -0.78    | -1.04 | -1.35    |
| Annual balance               | billion € p.a.    | 0                | 0.12  | 0.25  | 0.42     | 0.65  | 1.14     |
| <b>Terrestrial PV</b>        |                   |                  |       |       |          |       |          |
| Installed capacity           | GW <sub>p</sub>   | 2621             | 2069  | 1556  | 1044     | 533   | 0        |
| Generation sum               | TWh               | 5714             | 4510  | 3391  | 2276     | 1163  | 0        |
| Generation percentage        |                   | 100%             | 81.6% | 62.5% | 42.7%    | 22.2% | 0%       |
| Spec. installation costs     | €/kW <sub>p</sub> | 584              | 599   | 617   | 641      | 680   | 0        |
| Installation costs           | billion €         | 1530             | 1238  | 959   | 669      | 362   | 0        |
| O&M Costs                    | billion € p.a.    | 30.6             | 24.8  | 19.2  | 13.4     | 7.2   | 0        |
| Excess selling               | billion € p.a.    | -20.6            | -15.0 | -11.3 | -7.6     | -3.9  | 0        |
| Annual balance               | billion € p.a.    | 10.0             | 9.8   | 7.9   | 5.7      | 3.3   | 0        |
| <b>Storage: pumped hydro</b> |                   |                  |       |       |          |       |          |
| Max. power capacity          | GW                | 1828             | 1499  | 1203  | 908      | 614   | 359      |
| Energy capacity              | GWh               | 12475            | 12166 | 11096 | 10054    | 9025  | 7784     |
| Spec. installation costs     | €/kW              | 682              | 697   | 711   | 733      | 776   | 860      |
| Installation Costs           | billion €         | 1247             | 1045  | 855   | 665      | 477   | 309      |
| O&M Costs                    | billion € p.a.    | 9.58             | 7.52  | 5.46  | 3.42     | 1.57  | 0.44     |
| <b>Excess Generation</b>     |                   |                  |       |       |          |       |          |
| Excess generation            | TWh               | 825              | 734   | 725   | 717      | 705   | 692      |
| Revenues                     | billion € p.a.    | -20.6            | -18.4 | -18.1 | -17.9    | -17.6 | -17.3    |
| <b>Transmission lines</b>    |                   |                  |       |       |          |       |          |
| Transmission costs           | billion €         | 302              | 289   | 278   | 267      | 255   | 244      |
| AC transmission costs        | billion €         | 88               | 75    | 64    | 53       | 41    | 30       |
| O&M costs                    | billion € p.a.    | 3.0              | 2.9   | 2.8   | 2.7      | 2.6   | 2.4      |

## 8.2.5.2 Scenario 2

Table 208. Technical results and assumptions for cost calculation for scenario 2 at transport costs of 530 €/kg

| SPS system                               |                    | Terrestrial only |        | ...    | combined | ...    | SPS only |
|------------------------------------------|--------------------|------------------|--------|--------|----------|--------|----------|
| Number of SPS                            |                    | 0                | 15     | 30     | 45       | 60     | 83       |
| Space PV capacity                        | GW <sub>p</sub>    | 0                | 332    | 664    | 996      | 1328   | 1838     |
| Ground power out                         | GW <sub>p</sub>    | 0                | 118    | 236    | 353      | 471    | 652      |
| Generation sum                           | TWh                | 0                | 941    | 1882   | 2823     | 3764   | 5209     |
| Generation percentage                    |                    | 0                | 10.0%  | 22.6%  | 38.2%    | 58.5%  | 92.3%    |
| Spec. installation costs                 | €/kW <sub>p</sub>  | 0                | 8641   | 7612   | 7166     | 6866   | 6543     |
| Installation costs                       | billion €          | 0                | 1018   | 1794   | 2533     | 3236   | 4266     |
| O&M costs                                | billion € p.a.     | 0                | 6.11   | 10.76  | 15.20    | 19.41  | 25.60    |
| Excess selling                           | billion € p.a.     | 0                | -4.00  | -8.25  | -13.39   | -18.60 | -24.99   |
| Annual balance                           | billion € p.a.     | 0                | 2.11   | 2.51   | 1.81     | 0.81   | 0.61     |
| <b>SPS PV Reciever</b>                   |                    |                  |        |        |          |        |          |
| Installed capacity                       | GW <sub>p</sub>    | 0                | 42     | 85     | 127      | 170    | 238      |
| Generation sum                           | TWh                | 0                | 78     | 155    | 233      | 310    | 434      |
| Generation percentage                    |                    | 0                | 0.8%   | 1.9%   | 3.1%     | 4.8%   | 7.7%     |
| Spec. installation costs                 | €/kW <sub>p</sub>  | 0                | 546    | 564    | 587      | 624    | 748      |
| Installation costs                       | billion €          | 0                | 23     | 48     | 75       | 106    | 178      |
| O&M Costs                                | billion € p.a.     | 0                | 0.35   | 0.72   | 1.12     | 1.59   | 2.67     |
| Excess selling                           | billion € p.a.     | 0                | -0.33  | -0.68  | -1.10    | -1.53  | -2.08    |
| Annual balance                           | billion € p.a.     | 0                | 0.02   | 0.04   | 0.02     | 0.05   | 0.58     |
| <b>Terrestrial PV</b>                    |                    |                  |        |        |          |        |          |
| Installed capacity                       | GW <sub>p</sub>    | 4844             | 3832   | 2893   | 1987     | 1084   | 0        |
| Generation sum                           | TWh                | 10560            | 8354   | 6306   | 4331     | 2363   | 0        |
| Generation percentage                    |                    | 100%             | 89.1%  | 75.6%  | 58.6%    | 36.7%  | 0%       |
| Spec. installation costs                 | €/kW <sub>p</sub>  | 543              | 557    | 575    | 599      | 636    | 0        |
| Installation costs                       | billion €          | 2628             | 2135   | 1663   | 1189     | 690    | 0        |
| O&M Costs                                | billion € p.a.     | 52.56            | 42.70  | 33.26  | 23.78    | 13.79  | 0        |
| Excess selling                           | billion € p.a.     | -46.73           | -35.48 | -27.64 | -20.54   | -11.68 | 0        |
| Annual balance                           | billion € p.a.     | 5.83             | 7.23   | 5.61   | 3.24     | 2.12   | 0        |
| <b>Storage: hydrogen pressure vessel</b> |                    |                  |        |        |          |        |          |
| Max. power capacity                      | GW                 | 3718             | 2998   | 2339   | 1709     | 1082   | 420      |
| Energy capacity                          | GWh H <sub>2</sub> | 19509            | 19033  | 17568  | 15739    | 13904  | 9069     |
| Spec. installation costs                 | €/kW <sub>el</sub> | 484              | 506    | 534    | 576      | 667    | 928      |
| Installation Costs                       | billion €          | 1799             | 1518   | 1249   | 985      | 721    | 390      |
| O&M Costs                                | billion € p.a.     | 41.22            | 32.77  | 24.61  | 16.61    | 9.06   | 2.54     |
| <b>Excess Generation</b>                 |                    |                  |        |        |          |        |          |
| Excess generation                        | TWh <sub>el</sub>  | 1869             | 1592   | 1463   | 1401     | 1272   | 1083     |
| Revenues                                 | billion € p.a.     | -46.7            | -39.8  | -36.6  | -35.0    | -31.8  | -27.1    |
| <b>Transmission lines</b>                |                    |                  |        |        |          |        |          |
| Transmission costs                       | billion €          | 370              | 344    | 320    | 297      | 273    | 246      |
| AC transmission costs                    | billion €          | 157              | 131    | 106    | 83       | 59     | 32       |
| O&M costs                                | billion € p.a.     | 3.70             | 3.44   | 3.20   | 2.97     | 2.73   | 2.46     |

Table 209. Technical results and assumptions for cost calculation for scenario 2 at transport costs of 2650 €/kg

| SPS system                        |                    | Terrestrial only |        | ... | combined | ...    | SPS only         |        |
|-----------------------------------|--------------------|------------------|--------|-----|----------|--------|------------------|--------|
| Number of SPS                     |                    | 0                | 15     |     | 30       | 45     | 60               | 83     |
| Space PV capacity                 | GW <sub>p</sub>    | 0                | 332    |     | 664      | 996    | 1328             | 1838   |
| Ground power out                  | GW <sub>p</sub>    | 0                | 118    |     | 236      | 353    | 471              | 652    |
| Generation sum                    | TWh                | 0                | 941    |     | 1882     | 2823   | 3764             | 5209   |
| Generation percentage             |                    | 0                | 10.0%  |     | 22.6%    | 38.2%  | 58.5%            | 92.3%  |
| Spec. installation costs          | €/kW <sub>p</sub>  | 0                | 28550  |     | 25530    | 24013  | 22992            | 21893  |
| Installation costs                | billion €          | 0                | 3364   |     | 6016     | 8488   | 10836            | 14273  |
| O&M costs                         | billion € p.a.     | 0                | 20.18  |     | 36.10    | 50.93  | 65.01            | 85.64  |
| Excess selling                    | billion € p.a.     | 0                | -4.00  |     | -8.25    | -13.39 | -18.60           | -24.99 |
| Annual balance                    | billion € p.a.     | 0                | 16.19  |     | 27.85    | 37.54  | 46.41            | 60.65  |
| SPS PV Reciever                   |                    |                  |        |     |          |        |                  |        |
| Installed capacity                | GW <sub>p</sub>    | 0                | 42     |     | 85       | 127    | 170              | 238    |
| Generation sum                    | TWh                | 0                | 78     |     | 155      | 233    | 310              | 434    |
| Generation percentage             |                    | 0                | 0.8%   |     | 1.9%     | 3.1%   | 4.8%             | 7.7%   |
| Spec. installation costs          | €/kW <sub>p</sub>  | 0                | 546    |     | 564      | 587    | 624              | 748    |
| Installation costs                | billion €          | 0                | 23     |     | 48       | 75     | 106              | 178    |
| O&M Costs                         | billion € p.a.     | 0                | 0.35   |     | 0.72     | 1.12   | 1.59             | 2,67   |
| Excess selling                    | billion € p.a.     | 0                | -0.33  |     | -0.68    | -1.10  | -1.53            | -2,08  |
| Annual balance                    | billion € p.a.     | 0                | 0.02   |     | 0.04     | 0.02   | 0.05             | 0,58   |
| Terrestrial PV                    |                    |                  |        |     |          |        |                  |        |
| Installed capacity                | GW <sub>p</sub>    | 4844             | 3832   |     | 2893     | 1987   | 1084             | 0      |
| Generation sum                    | TWh                | 10560            | 8355   |     | 6306     | 4332   | 2363             | 0      |
| Generation percentage             |                    | 100%             | 89.1%  |     | 75.6%    | 58.6%  | 36.7%            | 0%     |
| Spec. installation costs          | €/kW <sub>p</sub>  | 543              | 557    |     | 575      | 599    | 636              | 0      |
| Installation costs                | billion €          | 2628             | 2135   |     | 1663     | 1189   | 690              | 0      |
| O&M Costs                         | billion € p.a.     | 52.56            | 42.71  |     | 33.26    | 23.79  | 13.79            | 0      |
| Excess selling                    | billion € p.a.     | -46.73           | -35.49 |     | -27.64   | -20.54 | -11.68           | 0      |
| Annual balance                    | billion € p.a.     | 5.83             | 7.22   |     | 5.61     | 3.24   | 2.12             | 0      |
| Storage: hydrogen pressure vessel |                    |                  |        |     |          |        |                  |        |
| Max. power capacity               | GW                 | 3718             | 2998   |     | 2339     | 1710   | 1082             | 420    |
| Energy capacity                   | GWh H <sub>2</sub> | 19509            | 19018  |     | 17568    | 15739  | 13904            | 9069   |
| Spec. installation costs          | €/kW <sub>el</sub> | 484              | 506    |     | 534      | 576    | 667              | 928    |
| Installation Costs                | billion €          | 1799             | 1518   |     | 1249     | 985    | 721              | 390    |
| O&M Costs                         | billion € p.a.     | 41.22            | 32.77  |     | 24.61    | 16.61  | 9.06             | 2.54   |
| Excess Generation                 |                    |                  |        |     |          |        |                  |        |
| Excess generation                 | TWh <sub>el</sub>  | 1869             | 1593   |     | 1463     | 1401   | 1272             | 1083   |
| Revenues                          | billion € p.a.     | -46.7            | -39.8  |     | -36.6    | -35.0  | -31.8            | -27.1  |
| Transmission lines                |                    |                  |        |     |          |        |                  |        |
| Transmission costs                | billion €          | 370              | 344    |     | 320      | 297    | 273              | 246    |
| AC transmission costs             | billion €          | 157              | 131    |     | 106      | 83     | 59 <sup>32</sup> |        |
| O&M costs                         | billion € p.a.     | 3.70             | 3.44   |     | 3.20     | 2.97   | 2.73             | 2.46   |

Table 210. Technical results and assumptions for cost calculation for scenario 2 at transport costs of 5300 €/kg.

| SPS system                        |                    |        |        |        |        |        |        |
|-----------------------------------|--------------------|--------|--------|--------|--------|--------|--------|
| Number of SPS                     |                    | 0      | 15     | 30     | 45     | 60     | 83     |
| Space PV capacity                 | GW <sub>p</sub>    | 0      | 332    | 664    | 996    | 1328   | 1838   |
| Ground power out                  | GW <sub>p</sub>    | 0      | 118    | 236    | 353    | 471    | 652    |
| Generation sum                    | TWh                | 0      | 941    | 1882   | 2823   | 3764   | 5209   |
| Generation percentage             |                    | 0      | 10.0%  | 22.6%  | 38.2%  | 58.5%  | 92.3%  |
| Spec. installation costs          | €/kW <sub>p</sub>  | 0      | 53437  | 47928  | 45071  | 43150  | 41081  |
| Installation costs                | billion €          | 0      | 6296   | 11294  | 15931  | 20336  | 26783  |
| O&M costs                         | billion € p.a.     | 0      | 37.78  | 67.76  | 95.59  | 122.01 | 160.70 |
| Excess selling                    | billion € p.a.     | 0      | -4.00  | -8.25  | -13.39 | -18.60 | -24.99 |
| Annual balance                    | billion € p.a.     | 0      | 33.78  | 59.51  | 82.20  | 103.41 | 135.71 |
| SPS PV Reciever                   |                    |        |        |        |        |        |        |
| Installed capacity                | GW <sub>p</sub>    | 0      | 42     | 85     | 127    | 170    | 238    |
| Generation sum                    | TWh                | 0      | 78     | 155    | 233    | 310    | 434    |
| Generation percentage             |                    | 0      | 0,8%   | 1,9%   | 3,1%   | 4,8%   | 7,7%   |
| Spec. installation costs          | €/kW <sub>p</sub>  | 0      | 546    | 564    | 587    | 624    | 748    |
| Installation costs                | billion €          | 0      | 23     | 48     | 75     | 106    | 178    |
| O&M Costs                         | billion € p.a.     | 0      | 0,35   | 0,72   | 1,12   | 1,59   | 2,67   |
| Excess selling                    | billion € p.a.     | 0      | -0,33  | -0,68  | -1,10  | -1,53  | -2,08  |
| Annual balance                    | billion € p.a.     | 0      | 0,02   | 0,04   | 0,02   | 0,05   | 0,58   |
| Terrestrial PV                    |                    |        |        |        |        |        |        |
| Installed capacity                | GW <sub>p</sub>    | 4844   | 3833   | 2893   | 1987   | 1084   | 0      |
| Generation sum                    | TWh                | 10560  | 8355   | 6306   | 4332   | 2363   | 0      |
| Generation percentage             |                    | 100%   | 89.1%  | 75.6%  | 58.6%  | 36.7%  | 0%     |
| Spec. installation costs          | €/kW <sub>p</sub>  | 543    | 557    | 575    | 599    | 636    | 0      |
| Installation costs                | billion €          | 2628   | 2135   | 1663   | 1189   | 690    | 0      |
| O&M Costs                         | billion € p.a.     | 52.56  | 42.71  | 33.26  | 23.79  | 13.79  | 0      |
| Excess selling                    | billion € p.a.     | -46.73 | -35.50 | -27.64 | -20.54 | -11.68 | 0      |
| Annual balance                    | billion € p.a.     | 5.83   | 7.21   | 5.61   | 3.24   | 2.12   | 0      |
| Storage: hydrogen pressure vessel |                    |        |        |        |        |        |        |
| Max. power capacity               | GW                 | 3718   | 2998   | 2339   | 1710   | 1082   | 420    |
| Energy capacity                   | GWh H <sub>2</sub> | 19509  | 19004  | 17568  | 15739  | 13904  | 9069   |
| Spec. installation costs          | €/kW <sub>el</sub> | 484    | 506    | 534    | 576    | 667    | 928    |
| Installation Costs                | billion €          | 1799   | 1518   | 1249   | 985    | 721    | 390    |
| O&M Costs                         | billion € p.a.     | 41.22  | 32.77  | 24.61  | 16.61  | 9.06   | 2.54   |
| Excess Generation                 |                    |        |        |        |        |        |        |
| Excess generation                 | TWh <sub>el</sub>  | 1869   | 1593   | 1463   | 1401   | 1272   | 1083   |
| Revenues                          | billion € p.a.     | -46.7  | -39.8  | -36.6  | -35.0  | -31.8  | -27.1  |
| Transmission lines                |                    |        |        |        |        |        |        |
| Transmission costs                | billion €          | 370    | 344    | 320    | 297    | 273    | 246    |
| AC transmission costs             | billion €          | 157    | 131    | 106    | 83     | 59     | 32     |
| O&M costs                         | billion € p.a.     | 3.70   | 3.44   | 3.20   | 2.97   | 2.73   | 2.46   |



### 8.2.5.3 Scenario 3

Table 211. Technical results and assumptions for cost calculation for scenario 3 at transport costs of 530 €/kg

| SPS system               |                   | Terrestrial only |        | ... | combined | ...    | SPS only |        |
|--------------------------|-------------------|------------------|--------|-----|----------|--------|----------|--------|
| Number of SPS            |                   | 0                | 15     |     | 30       | 45     | 60       | 78     |
| Space PV capacity        | GW <sub>p</sub>   | 0                | 332    |     | 664      | 996    | 1328     | 1727   |
| Ground power out         | GW <sub>p</sub>   | 0                | 118    |     | 236      | 353    | 471      | 613    |
| Generation sum           | TWh               | 0                | 983    |     | 1939     | 2867   | 3768     | 4813   |
| Generation percentage    |                   | 0                | 15.2%  |     | 31.6%    | 49.6%  | 69.7%    | 92.2%  |
| Spec. installation costs | €/kW <sub>p</sub> | 0                | 8641   |     | 7612     | 7166   | 6866     | 6604   |
| Installation costs       | billion €         | 0                | 1018   |     | 1794     | 2533   | 3236     | 4046   |
| O&M costs                | billion € p.a.    | 0                | 6.11   |     | 10.76    | 15.20  | 19.41    | 24.28  |
| Excess selling           | billion € p.a.    | 0                | -6.29  |     | -11.32   | -14.52 | -15.32   | -16.96 |
| Annual balance           | billion € p.a.    | 0                | -0.18  |     | -0.55    | 0.67   | 4.09     | 7.32   |
| SPS PV Reciever          |                   |                  |        |     |          |        |          |        |
| Installed capacity       | GW <sub>p</sub>   | 0                | 42     |     | 85       | 127    | 170      | 221    |
| Generation sum           | TWh               | 0                | 83     |     | 164      | 243    | 319      | 408    |
| Generation percentage    |                   | 0                | 1,3%   |     | 2,7%     | 4,2%   | 5,9%     | 7,8%   |
| Spec. installation costs | €/kW <sub>p</sub> | 0                | 568    |     | 586      | 611    | 653      | 754    |
| Installation costs       | billion €         | 0                | 24     |     | 50       | 78     | 111      | 166    |
| O&M Costs                | billion € p.a.    | 0                | 0.36   |     | 0.75     | 1.17   | 1.66     | 2.49   |
| Excess selling           | billion € p.a.    | 0                | -0.53  |     | -0.96    | -1.23  | -1.30    | -1.44  |
| Annual balance           | billion € p.a.    | 0                | -0.17  |     | -0.21    | -0.06  | 0.36     | 1.06   |
| Terrestrial PV           |                   |                  |        |     |          |        |          |        |
| Installed capacity       | GW <sub>p</sub>   | 3478             | 2756   |     | 2064     | 1366   | 676      | 0      |
| Generation sum           | TWh               | 6804             | 5392   |     | 4037     | 2673   | 1322     | 0      |
| Generation percentage    |                   | 100%             | 83.5%  |     | 65.8%    | 46.2%  | 24.4%    | 0%     |
| Spec. installation costs | €/kW <sub>p</sub> | 553              | 568    |     | 586      | 611    | 653      | 0      |
| Installation costs       | billion €         | 1924             | 1565   |     | 1209     | 835    | 441      | 0      |
| O&M Costs                | billion € p.a.    | 38.49            | 31.29  |     | 24.17    | 16.70  | 8.82     | 0      |
| Excess selling           | billion € p.a.    | -47.43           | -34.51 |     | -23.57   | -13.54 | -5.37    | 0      |
| Annual balance           | billion € p.a.    | -8.95            | -3.22  |     | 0.60     | 3.16   | 3.44     | 0      |
| Storage: pumped hydro    |                   |                  |        |     |          |        |          |        |
| Max. power capacity      | GW                | 2576             | 2092   |     | 1636     | 1176   | 734      | 374    |
| Energy capacity          | GWh               | 13549            | 11236  |     | 8807     | 8507   | 13217    | 15434  |
| Spec. installation costs | €/kW              | 663              | 664    |     | 665      | 687    | 816      | 1095   |
| Installation Costs       | billion €         | 1708             | 1390   |     | 1087     | 807    | 599      | 410    |
| O&M Costs                | billion € p.a.    | 9.65             | 7.42   |     | 5.28     | 3.26   | 1.52     | 0.42   |
| Excess Generation        |                   |                  |        |     |          |        |          |        |
| Excess generation        | TWh               | 1897             | 1653   |     | 1434     | 1172   | 880      | 736    |
| Revenues                 | billion € p.a.    | -47.4            | -41.3  |     | -35.8    | -29.3  | -22.0    | -18.4  |
| Transmission lines       |                   |                  |        |     |          |        |          |        |
| Transmission costs       | billion €         | 331              | 313    |     | 296      | 278    | 261      | 244    |
| AC transmission costs    | billion €         | 117              | 100    |     | 82       | 64     | 47       | 31     |
| O&M costs                | billion € p.a.    | 3.31             | 3.13   |     | 2.96     | 2.78   | 2.61     | 2.44   |

### 8.2.5.4 Scenario 4

Table 212. Technical results and assumptions for cost calculation for scenario 4 at transport costs of 530 €/kg

| SPS system                   |                   | Terrestrial only |        | ... | combined | ...    | SPS only |
|------------------------------|-------------------|------------------|--------|-----|----------|--------|----------|
| Number of SPS                |                   | 0                | 36     |     | 72       | 108    | 144      |
| Space PV capacity            | GW <sub>p</sub>   | 0                | 797    |     | 1594     | 2391   | 3188     |
| Ground power out             | GW <sub>p</sub>   | 0                | 283    |     | 566      | 848    | 1131     |
| Generation sum               | TWh               | 0                | 1282   |     | 2528     | 3740   | 4917     |
| Generation percentage        |                   | 0                | 21.0%  |     | 40.0%    | 56.8%  | 70.9%    |
| Spec. installation costs     | €/kW <sub>p</sub> | 0                | 7408   |     | 6683     | 6294   | 6033     |
| Installation costs           | billion €         | 0                | 2095   |     | 3779     | 5340   | 6824     |
| O&M costs                    | billion € p.a.    | 0                | 12.57  |     | 22.68    | 32.04  | 40.95    |
| Excess selling               | billion € p.a.    | 0                | -7.00  |     | -16.69   | -28.58 | -42.42   |
| Annual balance               | billion € p.a.    | 0                | 5.57   |     | 5.98     | 3.46   | -1.47    |
| <b>SPS PV Reciever</b>       |                   |                  |        |     |          |        |          |
| Installed capacity           | GW <sub>p</sub>   | 0                | 102    |     | 204      | 305    | 407      |
| Generation sum               | TWh               | 0                | 211    |     | 418      | 620    | 817      |
| Generation percentage        |                   | 0                | 3.5%   |     | 6.6%     | 9.4%   | 11.8%    |
| Spec. installation costs     | €/kW <sub>p</sub> | 0                | 595    |     | 612      | 632    | 656      |
| Installation costs           | billion €         | 0                | 61     |     | 125      | 193    | 267      |
| O&M Costs                    | billion € p.a.    | 0                | 0.91   |     | 1.87     | 2.90   | 4.01     |
| Excess selling               | billion € p.a.    | 0                | -1.15  |     | -2.76    | -4.73  | -7.05    |
| Annual balance               | billion € p.a.    | 0                | -0.24  |     | -0.89    | -1.84  | -3.04    |
| <b>Terrestrial PV</b>        |                   |                  |        |     |          |        |          |
| Installed capacity           | GW <sub>p</sub>   | 2706             | 2123   |     | 1554     | 1024   | 553      |
| Generation sum               | TWh               | 5870             | 4606   |     | 3371     | 2222   | 1200     |
| Generation percentage        |                   | 100%             | 75.5%  |     | 53.4%    | 33.8%  | 17.3%    |
| Spec. installation costs     | €/kW <sub>p</sub> | 581              | 595    |     | 612      | 632    | 656      |
| Installation costs           | billion €         | 1573             | 1263   |     | 950      | 647    | 363      |
| O&M Costs                    | billion € p.a.    | 31.46            | 25.27  |     | 19.01    | 12.95  | 7.26     |
| Excess selling               | billion € p.a.    | -24.40           | -25.15 |     | -22.26   | -16.98 | -10.35   |
| Annual balance               | billion € p.a.    | 7.06             | 0.12   |     | -3.25    | -4.04  | -3.09    |
| <b>Storage: pumped hydro</b> |                   |                  |        |     |          |        |          |
| Max. power capacity          | GW                | 1900             | 1646   |     | 1396     | 1184   | 1034     |
| Energy capacity              | GWh               | 12185            | 10749  |     | 9906     | 9196   | 8193     |
| Spec. installation costs     | €/kW              | 677              | 678    |     | 685      | 693    | 695      |
| Installation Costs           | billion €         | 1287             | 1116   |     | 957      | 821    | 719      |
| O&M Costs                    | billion € p.a.    | 9.61             | 6.67   |     | 3.93     | 2.03   | 1.20     |
| <b>Excess Generation</b>     |                   |                  |        |     |          |        |          |
| Excess generation            | TWh               | 976              | 1332   |     | 1668     | 2012   | 2393     |
| Revenues                     | billion € p.a.    | -24.4            | -33.3  |     | -41.7    | -50.3  | -59.8    |
| <b>Transmission lines</b>    |                   |                  |        |     |          |        |          |
| Transmission costs           | billion €         | 304              | 294    |     | 285      | 277    | 271      |
| AC transmission costs        | billion €         | 91               | 80     |     | 71       | 63     | 57       |
| O&M costs                    | billion € p.a.    | 3.04             | 2.94   |     | 2.85     | 2.77   | 2.71     |

## 8.2.6 Hydrogen production

### 8.2.6.1 Hydrogen production today

#### 8.2.6.1.1 Scenario A (Generation with Solar Thermal Power and electrolysis) today

Table 213. Technical Results and assumption for cost calculations

|                                 |                                                                          |
|---------------------------------|--------------------------------------------------------------------------|
| <b>H<sub>2</sub>-Generation</b> |                                                                          |
| Input Energy                    | 876 TWh<br>237 billion m <sup>3</sup>                                    |
| Input Power                     | 100 GW<br>27 million m <sup>3</sup> /h                                   |
| Output Energy                   | 560 TWh                                                                  |
| Output Power                    | 64 GW                                                                    |
| <b>ST Generation</b>            |                                                                          |
| Average Production              | 140 GW <sub>el</sub>                                                     |
| LEC at 6%                       | 0.040 €/kWh <sub>el</sub><br>0.088 €/kWh <sub>H<sub>2</sub> output</sub> |
| LEC at 8%                       | 0.046 €/kWh <sub>el</sub><br>0.101 €/kWh <sub>H<sub>2</sub> output</sub> |
| <b>Transmission</b>             |                                                                          |
| Length                          | 5,000 km                                                                 |
| Capacity                        | 3 x 84 billion m <sup>3</sup> /a                                         |
| Costs                           | 30 billion €                                                             |
| Lifetime                        | 50 years                                                                 |
| O&M costs                       | 0.03 billion € p.a.                                                      |
| Losses                          | 36%                                                                      |
| <b>Buffer storage</b>           |                                                                          |
| Capacity                        | 650 million m <sup>3</sup><br>2.3 TWh                                    |
| Costs                           | 0.72 billion €                                                           |
| Lifetime                        | 50 years                                                                 |
| O&M costs                       | 0.007 billion € p.a.                                                     |
| <b>Electrolysis</b>             |                                                                          |
| Capacity                        | 140 GW <sub>el</sub>                                                     |
| Efficiency                      | 73%                                                                      |
| Costs                           | 900 €/kW<br>126 billion €                                                |
| Lifetime                        | 20 years                                                                 |
| O&M costs                       | 2.52 billion € p.a.                                                      |

Table 214. Cost calculations.

|                                |                           |
|--------------------------------|---------------------------|
| <b>Resulting LEC</b>           |                           |
| Interest rate 6%               | 0.114 €/kWh <sub>H2</sub> |
| Interest rate 8%               | 0.131 €/kWh <sub>H2</sub> |
| <b>LEC Breakdown for IR=6%</b> |                           |
| ST generation                  | 35.2%                     |
| Electrolysis                   | 38.4%                     |
| Transmission and buffer        | 26.4%                     |

## 8.2.6.2 Hydrogen production in 2020/2030

### 8.2.6.2.1 Scenario A (Generation with Solar Thermal Power and electrolysis) in 2020/2030

Table 215. Technical Results and assumption for cost calculations

|                                 |                                        |
|---------------------------------|----------------------------------------|
| <b>H<sub>2</sub>-Generation</b> |                                        |
| Input Energy                    | 876 TWh<br>237 billion m <sup>3</sup>  |
| Input Power                     | 100 GW<br>27 million m <sup>3</sup> /h |
| Output Energy                   | 735 TWh                                |
| Output Power                    | 84 GW                                  |
| <b>ST Generation</b>            |                                        |
| Average Production              | 130 GW <sub>el</sub>                   |
| LEC at 6%                       | 0.036 €/kWh <sub>el</sub>              |
| LEC at 8%                       | 0.041 €/kWh <sub>el</sub>              |
| <b>Transmission</b>             |                                        |
| Length                          | 5,000 km                               |
| Capacity                        | 160 billion m <sup>3</sup> /a          |
| Costs                           | 17.5 billion €                         |
| Lifetime                        | 50 years                               |
| O&M costs                       | 0.02 billion € p.a.                    |
| Losses                          | 16%                                    |
| <b>Buffer storage</b>           |                                        |
| Capacity                        | 650 million m <sup>3</sup><br>2.3 TWh  |
| Costs                           | 0.72 billion €                         |
| Lifetime                        | 50 years                               |
| O&M costs                       | 0.007 billion € p.a.                   |
| <b>Electrolysis</b>             |                                        |
| Capacity                        | 130 GW <sub>el</sub>                   |
| Efficiency                      | 77 %                                   |
| Costs                           | 850 €/kW<br>111 billion €              |
| Lifetime                        | 20 years                               |
| O&M costs                       | 2.22 billion € p.a.                    |

Table 216. Cost calculations

|                                |                           |
|--------------------------------|---------------------------|
| <b>Resulting LEC</b>           |                           |
| Interest rate 6%               | 0.074 €/kWh <sub>H2</sub> |
| Interest rate 8%               | 0.084 €/kWh <sub>H2</sub> |
| <b>LEC Breakdown for IR=6%</b> |                           |
| ST generation                  | 48.9%                     |
| Electrolysis                   | 37.7%                     |
| Transmission and buffer        | 13.4%                     |

## 8.3 Addendum to Life Cycle Assessment

### 8.3.1 Input Data for the Terrestrial Systems

#### Base-load, photovoltaics

|                                                                            |
|----------------------------------------------------------------------------|
| Data in this area is being imported FROM Umberto.                          |
| Data in this area is being imported TO Umberto.                            |
| Data in this area refers TO another excel-sheet in this file.              |
| Data in this area is being referred FROM another excel-sheet in this file. |

Input data refer to DLR 2004

|                                                |     | state-of-the-art   |               |                |                 |                 | 2020/2030          |               |                |                 |                 | 2030 dynamic        |                   |                    |                     |                     |
|------------------------------------------------|-----|--------------------|---------------|----------------|-----------------|-----------------|--------------------|---------------|----------------|-----------------|-----------------|---------------------|-------------------|--------------------|---------------------|---------------------|
| Baseload                                       | GW  | 0.5                | 5             | 10             | 100             | 150             | 0.5                | 5             | 10             | 100             | 150             | 0.5                 | 5                 | 10                 | 100                 | 150                 |
| EI. delivered to the grid                      | TWh | 4.38               | 43.8          | 87.6           | 876             | 1314            | 4.38               | 43.8          | 87.6           | 876             | 1314            | 4.38                | 43.8              | 87.6               | 876                 | 1314                |
| Identification code                            | MJ  | 1.58E+10           | 1.58E+11      | 3.15E+11       | 3.15E+12        | 4.73E+12        | 1.58E+10           | 1.58E+11      | 3.15E+11       | 3.15E+12        | 4.73E+12        | 1.58E+10            | 1.58E+11          | 3.15E+11           | 3.15E+12            | 4.73E+12            |
|                                                |     | Base_PV_S_0.5GW    | Base_PV_S_5GW | Base_PV_S_10GW | Base_PV_S_100GW | Base_PV_S_150GW | Base_PV_F_0.5GW    | Base_PV_F_5GW | Base_PV_F_10GW | Base_PV_F_100GW | Base_PV_F_150GW | Base_PV_F_0.5GW_dyn | Base_PV_F_5GW_dyn | Base_PV_F_10GW_dyn | Base_PV_F_100GW_dyn | Base_PV_F_150GW_dyn |
| <b>PV</b>                                      |     |                    |               |                |                 |                 |                    |               |                |                 |                 |                     |                   |                    |                     |                     |
| PV_Capacity                                    | GW  | 3                  | 33            | 65             | 653             | 997             | 3                  | 30            | 55             | 553             | 846             | 3                   | 30                | 55                 | 553                 | 846                 |
| PV_Cap_Umberto (share!)                        | GW  | 0.1                | 0.1           | 0.1            | 0.1             | 0.1             | 0.1                | 0.1           | 0.1            | 0.1             | 0.1             | 0.1                 | 0.1               | 0.1                | 0.1                 | 0.1                 |
| PV_Generation                                  | TWh | 5.51               | 60.62         | 146.91         | 1,451.32        | 2,243.50        | 5.79               | 67.87         | 123.95         | 1,230.48        | 1,908.67        | 5.79                | 67.87             | 123.95             | 1,230.48            | 1,908.67            |
| ...for export                                  | TWh | 5.51               | 60.62         | 134.44         | 1,350.56        | 2,062.00        | 5.79               | 67.87         | 113.75         | 1,143.74        | 1,749.74        | 5.79                | 67.87             | 113.75             | 1,143.74            | 1,749.74            |
| ...for excess                                  | TWh |                    |               | 12.47          | 100.76          | 181.50          |                    |               | 10.20          | 86.74           | 158.93          |                     |                   | 10.20              | 86.74               | 158.93              |
| eta_module_PV                                  | %   | 14.0               | 14.0          | 14.0           | 14.0            | 14.0            | 15.0               | 15.0          | 15.0           | 15.0            | 15.0            | 15.0                | 15.0              | 15.0               | 15.0                | 15.0                |
| PV_Lifetime                                    | a   | 25                 | 25            | 25             | 25              | 25              | 25                 | 25            | 25             | 25              | 25              | 25                  | 25                | 25                 | 25                  | 25                  |
| eta_module_PV model                            | %   | 13                 | 13            | 13             | 13              | 13              | 9                  | 9             | 9              | 9               | 9               | 9                   | 9                 | 9                  | 9                   | 9                   |
| PV_Lifetime model                              | a   | 25                 | 25            | 25             | 25              | 25              | 20                 | 20            | 20             | 20              | 20              | 20                  | 20                | 20                 | 20                  | 20                  |
| CED, non-renewable (share!)                    |     |                    | 2.82E+09      |                |                 |                 |                    | 9.94E+08      |                |                 |                 |                     | 7.55E+08          |                    |                     |                     |
| CED, non-renewable, change of eta              | MJ  |                    | 2.62E+09      |                |                 |                 |                    | 5.96E+08      |                |                 |                 |                     | 4.53E+08          |                    |                     |                     |
| CED in system lifetime                         | MJ  |                    | 3.14E+09      |                |                 |                 |                    | 8.95E+08      |                |                 |                 |                     | 6.80E+08          |                    |                     |                     |
| CED, non-renewable                             | MJ  | 9.43E+10           | 1.04E+12      | 2.04E+12       | 2.05E+13        | 3.13E+13        | 2.68E+10           | 2.68E+11      | 4.92E+11       | 4.95E+12        | 7.57E+12        | 2.04E+10            | 2.04E+11          | 3.74E+11           | 3.76E+12            | 5.75E+12            |
| MJ/kw                                          |     |                    |               |                |                 |                 |                    |               |                |                 |                 |                     |                   |                    |                     |                     |
| <b>Lines to storage (HVAC)</b>                 |     |                    |               |                |                 |                 |                    |               |                |                 |                 |                     |                   |                    |                     |                     |
| Stor_distance_HVAC_10GW                        | km  |                    |               | 350            | 350             | 350             |                    |               | 350            | 350             | 350             |                     |                   | 350                | 350                 | 350                 |
| eta_stor_distance                              | %   |                    |               | 98.5           | 98.5            | 98.5            |                    |               | 98.5           | 98.5            | 98.5            |                     |                   | 98.5               | 98.5                | 98.5                |
| CED, non-renewable                             | MJ  |                    | 8.39E+08      |                | 8.39E+08        | 8.39E+08        |                    | 8.39E+08      |                | 8.39E+08        | 8.39E+08        |                     | 5.00E+08          |                    | 5.00E+08            | 5.00E+08            |
| no modification compared with state-of-the-art |     |                    |               |                |                 |                 |                    |               |                |                 |                 |                     |                   |                    |                     |                     |
| <b>Hydro pump storage</b>                      |     |                    |               |                |                 |                 |                    |               |                |                 |                 |                     |                   |                    |                     |                     |
| Stor_Capacity                                  | GW  | 2.1                | 23.65         | 42.51          | 424.77          | 651.1           | 2.25               | 21.93         | 36.86          | 369.02          | 567.18          | 2.25                | 21.93             | 36.86              | 369.02              | 567.18              |
| Stor_output                                    | TWh | 3.13E+00           | 4.60E+01      | 9.30E+01       | 8.43E+02        | 1.35E+03        | 7.48E+00           | 1.28E+02      | 8.37E+01       | 7.29E+02        | 1.24E+03        | 7.48E+00            | 1.28E+02          | 8.37E+01           | 7.29E+02            | 1.24E+03            |
| eta_stor                                       | %   | 75.00%             | 75.00%        | 75.00%         | 75.00%          | 75.00%          | 85.00%             | 85.00%        | 85.00%         | 85.00%          | 85.00%          | 85.00%              | 85.00%            | 85.00%             | 85.00%              | 85.00%              |
| Stor_Lifetime                                  | a   | 40                 | 40            | 40             | 40              | 40              | 40                 | 40            | 40             | 40              | 40              | 40                  | 40                | 40                 | 40                  | 40                  |
| CED, non-renewable                             | MJ  | 1.05E+08           | 1.55E+09      | 3.13E+09       | 2.83E+10        | 4.54E+10        | 2.52E+08           | 4.30E+09      | 2.81E+09       | 2.45E+10        | 4.16E+10        | 2.05E+08            | 3.50E+09          | 2.29E+09           | 2.00E+10            | 3.39E+10            |
| Values linearly extrapolated from base load ST |     |                    |               |                |                 |                 |                    |               |                |                 |                 |                     |                   |                    |                     |                     |
| <b>Transmission lines (HVDC)</b>               |     |                    |               |                |                 |                 |                    |               |                |                 |                 |                     |                   |                    |                     |                     |
| Trans_distance_HVDC                            | km  | Use of exist. line | 6,000         | 12,200         | 121,400         | 196,900         | Use of exist. line | 6,000         | 8,400          | 91,300          | 142,300         | Use of exist. lines | 6,000             | 8,400              | 91,300              | 142,300             |
| eta_trans_HVDC                                 | %   | 98.00%             | 96.70%        | 84.70%         | 81.90%          | 81.50%          | 98.00%             | 96.70%        | 88.50%         | 86.30%          | 85.80%          | 98.00%              | 96.70%            | 88.50%             | 86.30%              | 85.80%              |
| HVDC_load                                      | GW  | 5.0                | 5.0           | 5.0            | 5.0             | 5.0             | 6.5                | 6.5           | 6.5            | 6.5             | 6.5             | 6.5                 | 6.5               | 6.5                | 6.5                 | 6.5                 |
| HVDC stations                                  |     |                    | 3             | 23             | 36              |                 |                    | 2             | 18             | 26              |                 |                     | 2                 | 18                 | 26                  |                     |
| Trans_Lifetime                                 | a   |                    | 50            | 50             | 50              | 50              |                    | 50            | 50             | 50              | 50              |                     | 50                | 50                 | 50                  | 50                  |
| CED, non-renewable                             | MJ  |                    | 2.42E+10      | 4.93E+10       | 4.90E+11        | 7.95E+11        |                    | 3.11E+10      | 4.36E+10       | 4.74E+11        | 7.39E+11        |                     | 2.35E+10          | 3.29E+10           | 3.58E+11            | 5.58E+11            |
| Values linearly extrapolated from base load ST |     |                    |               |                |                 |                 |                    |               |                |                 |                 |                     |                   |                    |                     |                     |
| Source                                         |     | Tab. 51-53         | Tab. 56-58    | Tab. 62-65     | Tab. 59-72      | Tab. 76-79      | Tab. 83-84         | Tab. 87-88    | Tab. 91-94     | Tab. 97-100     | Tab. 104-107    | Tab. 83-84          | Tab. 87-88        | Tab. 91-94         | Tab. 97-100         | Tab. 104-107        |
| CED, non-renewable                             | MJ  | 9.44E+10           | 1.06E+12      | 2.10E+12       | 2.10E+13        | 3.22E+13        | 2.71E+10           | 3.04E+11      | 5.39E+11       | 5.45E+12        | 8.35E+12        | 2.06E+10            | 2.31E+11          | 4.10E+11           | 4.14E+12            | 6.34E+12            |
| EPT (energy payback time)                      | m   | 2.39E+00           | 2.70E+00      | 2.66E+00       | 2.67E+00        | 2.72E+00        | 6.87E-01           | 7.71E-01      | 6.84E-01       | 6.91E-01        | 7.06E-01        | 6.87E-01            | 7.71E-01          | 6.83E-01           | 6.90E-01            | 7.05E-01            |
|                                                |     | 28.7               | 32.4          | 31.9           | 32.0            | 32.6            | 8.2                | 9.2           | 8.2            | 8.3             | 8.5             | 8.2                 | 9.2               | 8.2                | 8.3                 | 8.5                 |
| Share PV                                       | %   | 99.89%             | 97.57%        | 97.46%         | 97.53%          | 97.38%          | 99.07%             | 88.33%        | 91.24%         | 90.83%          | 90.65%          | 99.01%              | 88.30%            | 91.28%             | 90.85%              | 90.66%              |
| Share Lines_to_storage                         | %   | 0.00%              | 0.00%         | 0.04%          | 0.00%           | 0.00%           | 0.00%              | 0.00%         | 0.16%          | 0.02%           | 0.01%           | 0.00%               | 0.00%             | 0.12%              | 0.01%               | 0.01%               |
| Share Storage                                  | %   | 0.11%              | 0.15%         | 0.15%          | 0.13%           | 0.14%           | 0.93%              | 1.42%         | 0.52%          | 0.45%           | 0.50%           | 0.99%               | 1.52%             | 0.56%              | 0.48%               | 0.53%               |
| Share Transmission lines                       | %   | 0.00%              | 2.28%         | 2.35%          | 2.33%           | 2.47%           | 0.00%              | 10.25%        | 8.08%          | 8.70%           | 8.85%           | 0.00%               | 10.19%            | 8.04%              | 8.65%               | 8.80%               |

## Base-load, solar thermal

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 Data in this area is being referred FROM another excel-sheet in this file.

Input data refer to DLR 2004

|                                        |  | state-of-the-art |                                                         |               |                |                 | 2020/2030       |                                                         |               |                |                 | 2030 dynamic    |                                                         |                   |                    |                     |                     |
|----------------------------------------|--|------------------|---------------------------------------------------------|---------------|----------------|-----------------|-----------------|---------------------------------------------------------|---------------|----------------|-----------------|-----------------|---------------------------------------------------------|-------------------|--------------------|---------------------|---------------------|
| Baseload                               |  | GW               | 0.5                                                     | 5             | 10             | 100             | 150             | 0.5                                                     | 5             | 10             | 100             | 150             | 0.5                                                     | 5                 | 10                 | 100                 | 150                 |
| El. delivered to the grid              |  | TWh              | 4.38                                                    | 43.8          | 87.6           | 876             | 1314            | 4.38                                                    | 43.8          | 87.6           | 876             | 1314            | 4.38                                                    | 43.8              | 87.6               | 876                 | 1314                |
| Identification code                    |  | MJ               | 1.58E+10                                                | 1.58E+11      | 3.15E+11       | 3.15E+12        | 4.73E+12        | 1.58E+10                                                | 1.58E+11      | 3.15E+11       | 3.15E+12        | 4.73E+12        | 1.58E+10                                                | 1.58E+11          | 3.15E+11           | 3.15E+12            | 4.73E+12            |
|                                        |  |                  | Base_ST_S_0.5GW                                         | Base_ST_S_5GW | Base_ST_S_10GW | Base_ST_S_100GW | Base_ST_S_150GW | Base_ST_F_0.5GW                                         | Base_ST_F_5GW | Base_ST_F_10GW | Base_ST_F_100GW | Base_ST_F_150GW | Base_ST_F_0.5GW_dyn                                     | Base_ST_F_5GW_dyn | Base_ST_F_10GW_dyn | Base_ST_F_100GW_dyn | Base_ST_F_150GW_dyn |
| ST                                     |  |                  |                                                         |               |                |                 |                 |                                                         |               |                |                 |                 |                                                         |                   |                    |                     |                     |
| ST_Capacity                            |  | GW               | 0.75                                                    | 7.7           | 15.5           | 150             | 220             | 0.73                                                    | 7.5           | 15.1           | 138             | 208             | 0.73                                                    | 7.5               | 15.1               | 138                 | 208                 |
| ST_Cap_Umberto (share!)                |  | GW               | 0.1                                                     | 0.1           | 0.1            | 0.1             | 0.1             | 0.1                                                     | 0.1           | 0.1            | 0.1             | 0.1             | 0.1                                                     | 0.1               | 0.1                | 0.1                 | 0.1                 |
| ST_field size                          |  | m2               | 17,800,000                                              | 182,600,000   | 367,500,000    | 3,556,500,000   | 5,216,000,000   | 16,400,000                                              | 168,900,000   | 340,100,000    | 3,107,800,000   | 4,684,200,000   | 16,400,000                                              | 168,900,000       | 340,100,000        | 3,107,800,000       | 4,684,200,000       |
| ST_field size_Umberto (share!)         |  | m2               | 2,373,333                                               | 2,371,429     | 2,370,968      | 2,371,000       | 2,370,909       | 2,246,575                                               | 2,252,000     | 2,252,318      | 2,252,029       | 2,252,019       | 2,246,575                                               | 2,252,000         | 2,252,318          | 2,252,029           | 2,252,019           |
| ST_thermal_stor                        |  | GW <sub>th</sub> | 46.3                                                    | 475.1         | 956.4          | 9,255           | 13,574          | 42.8                                                    | 439.7         | 885.2          | 8,089           | 12,193          | 42.8                                                    | 439.7             | 885.2              | 8,089               | 12,193              |
| ST_thermal_stor                        |  | h                | 24.0                                                    | 24.0          | 24.0           | 24.0            | 24.0            | 24.0                                                    | 24.0          | 24.0           | 24.0            | 24.0            | 24.0                                                    | 24.0              | 24.0               | 24.0                | 24.0                |
| ST_thermal_stor_Umberto (share!)       |  | GW <sub>th</sub> | 0.257                                                   | 0.257         | 0.257          | 0.257           | 0.257           | 0.244                                                   | 0.244         | 0.244          | 0.244           | 0.244           | 0.244                                                   | 0.244             | 0.244              | 0.244               | 0.244               |
| ST_Generation                          |  | TWh              | 5.046                                                   | 51.033        | 102.86         | 1,142.50        | 1,757           | 4.914                                                   | 50.483        | 100.2          | 1,102.50        | 1,662           | 4.914                                                   | 50.483            | 100.2              | 1,102.50            | 1,662               |
| eta_PB                                 |  | %                | 33.00%                                                  | 33.00%        | 33.00%         | 33.00%          | 33.00%          | 33.00%                                                  | 33.00%        | 33.00%         | 33.00%          | 33.00%          | 33.00%                                                  | 33.00%            | 33.00%             | 33.00%              | 33.00%              |
| eta_ST                                 |  | %                | 32.70%                                                  | 32.70%        | 32.70%         | 32.70%          | 32.70%          | 36.10%                                                  | 36.10%        | 36.10%         | 36.10%          | 36.10%          | 36.10%                                                  | 36.10%            | 36.10%             | 36.10%              | 36.10%              |
| ST_DNI_Umberto                         |  | kWh/m2           | 2,627                                                   | 2,590         | 2,594          | 2,977           | 3,122           | 2,515                                                   | 2,509         | 2,473          | 2,978           | 2,978           | 2,515                                                   | 2,509             | 2,473              | 2,978               | 2,978               |
| ST_Lifetime                            |  | a                | 30                                                      | 30            | 30             | 30              | 30              | 30                                                      | 30            | 30             | 30              | 30              | 30                                                      | 30                | 30                 | 30                  | 30                  |
| CED, non-renew. (share!) , constructio |  | MJ               |                                                         | 3.20E+09      |                |                 |                 |                                                         | 3.05E+09      |                |                 |                 |                                                         | 1.95E+09          |                    |                     |                     |
| CED, non-renew. (share!) , maintenanc  |  | MJ               |                                                         | 6.71E+08      |                |                 |                 |                                                         | 6.37E+08      |                |                 |                 |                                                         | 6.35E+08          |                    |                     |                     |
| CED, non-renewable, construction       |  | MJ               | 2.40E+10                                                | 2.47E+11      | 4.96E+11       | 4.80E+12        | 7.05E+12        | 2.23E+10                                                | 2.29E+11      | 4.60E+11       | 4.21E+12        | 6.34E+12        | 1.43E+10                                                | 1.47E+11          | 2.95E+11           | 2.70E+12            | 4.06E+12            |
| CED, non-renewable, maintenance        |  | MJ               | 5.04E+09                                                | 5.17E+10      | 1.04E+11       | 1.01E+12        | 1.48E+12        | 4.65E+09                                                | 4.78E+10      | 9.62E+10       | 8.79E+11        | 1.33E+12        | 4.64E+09                                                | 4.76E+10          | 9.59E+10           | 8.77E+11            | 1.32E+12            |
|                                        |  |                  | Values linearly extrapolated from 0,1 GW to ST_capacity |               |                |                 |                 | Values linearly extrapolated from 0,1 GW to ST_capacity |               |                |                 |                 | Values linearly extrapolated from 0,1 GW to ST_capacity |                   |                    |                     |                     |
| Lines to storage (HVAC)                |  |                  |                                                         |               |                |                 |                 |                                                         |               |                |                 |                 |                                                         |                   |                    |                     |                     |
| Stor_distance_HVAC_10GW                |  | km               |                                                         |               |                |                 |                 |                                                         |               |                |                 |                 |                                                         |                   |                    |                     |                     |
| eta_stor_distance                      |  | %                |                                                         |               |                |                 |                 |                                                         |               |                |                 |                 |                                                         |                   |                    |                     |                     |
| CED, non-renewable                     |  | MJ               |                                                         |               |                |                 |                 |                                                         |               |                |                 |                 |                                                         |                   |                    |                     |                     |
| Hydro pump storage                     |  |                  |                                                         |               |                |                 |                 |                                                         |               |                |                 |                 |                                                         |                   |                    |                     |                     |
| Stor_Capacity                          |  | GW               | 0.5                                                     | 5             | 10             | 31.8            | 47.4            | 0.5                                                     | 5             | 10             | 31.9            | 47.6            | 0.5                                                     | 5                 | 10                 | 31.9                | 47.6                |
| Stor_output                            |  | TWh              | 1.73E+00                                                | 1.7215E+01    | 2.69E+01       | 2.23E+02        | 4.28E+02        | 2.52E+00                                                | 2.9400E+01    | 3.58E+01       | 4.89E+02        | 7.49E+02        | 2.52E+00                                                | 2.9400E+01        | 3.58E+01           | 4.89E+02            | 7.49E+02            |
| eta_stor                               |  | %                | 75.00%                                                  | 75.00%        | 75.00%         | 75.00%          | 75.00%          | 85.00%                                                  | 85.00%        | 85.00%         | 85.00%          | 85.00%          | 85.00%                                                  | 85.00%            | 85.00%             | 85.00%              | 85.00%              |
| Stor_Lifetime                          |  | a                | 40                                                      | 40            | 40             | 40              | 40              | 40                                                      | 40            | 40             | 40              | 40              | 40                                                      | 40                | 40                 | 40                  | 40                  |
| CED, non-renewable                     |  | MJ               | 5.82E+07                                                | 5.79E+08      | 9.05E+08       | 7.49E+09        | 1.44E+10        | 8.47E+07                                                | 9.89E+08      | 1.20E+09       | 1.64E+10        | 2.52E+10        | 6.90E+07                                                | 8.05E+08          | 9.79E+08           | 1.34E+10            | 2.05E+10            |
|                                        |  |                  | Values linearly extrapolated from base load ST          |               |                |                 |                 | Values linearly extrapolated from base load ST          |               |                |                 |                 | Values linearly extrapolated from base load ST          |                   |                    |                     |                     |
| Transmission lines (HVDC)              |  |                  |                                                         |               |                |                 |                 |                                                         |               |                |                 |                 |                                                         |                   |                    |                     |                     |
| Trans_distance_HVDC                    |  | km               | Use of exist.lin                                        | 2,000         | 9,800          | 140,600         | 219,300         | Use of exist.lin                                        | 2,000         | 9,800          | 102,500         | 162,000         | Use of exist.lines                                      | 2,000             | 9,800              | 102,500             | 162,000             |
| eta_trans_HVDC                         |  | %                | 98.00%                                                  | 96.70%        | 93.30%         | 82.00%          | 81.40%          | 98.00%                                                  | 96.70%        | 93.30%         | 86.20%          | 85.90%          | 98.00%                                                  | 96.70%            | 93.30%             | 86.20%              | 85.90%              |
| HVDC_load                              |  | GW               | 5.0                                                     | 5.0           | 5.0            | 5.0             | 5.0             | 6.5                                                     | 6.5           | 6.5            | 6.5             | 6.5             | 6.5                                                     | 6.5               | 6.5                | 6.5                 | 6.5                 |
| HVDC stations                          |  |                  |                                                         |               |                |                 |                 |                                                         |               |                |                 |                 |                                                         |                   |                    |                     |                     |
| Trans_Lifetime                         |  | a                |                                                         | 50            | 50             | 50              | 50              |                                                         | 50            | 50             | 50              | 50              |                                                         | 50                | 50                 | 50                  | 50                  |
| CED, non-renewable                     |  | MJ               | 0.00E+00                                                | 8.08E+09      | 3.96E+10       | 5.68E+11        | 8.86E+11        | 0.00E+00                                                | 1.04E+10      | 50862000000    | 5.31975E+11     | 8.4078E+11      | 0.00E+00                                                | 7.84E+09          | 3.84E+10           | 4.02E+11            | 6.35E+11            |
|                                        |  |                  | Values linearly extrapolated from base load ST          |               |                |                 |                 | Values linearly extrapolated from base load ST          |               |                |                 |                 | Values linearly extrapolated from base load ST          |                   |                    |                     |                     |
| Source                                 |  |                  | Tab. 54-55                                              | Tab. 59-61    | Tab. 66-68     | Tab. 73-75      | Tab. 80-82      | Tab. 85-86                                              | Tab. 89-90    | Tab. 95-96     | Tab. 101-103    | Tab. 108-110    | Tab. 85-86                                              | Tab. 89-90        | Tab. 95-96         | Tab. 101-103        | Tab. 108-110        |
| CED, non-renew., construction          |  | MJ               | 2.41E+10                                                | 2.55E+11      | 5.37E+11       | 5.38E+12        | 7.95E+12        | 2.23E+10                                                | 2.40E+11      | 5.12E+11       | 4.75E+12        | 7.21E+12        | 1.43E+10                                                | 1.55E+11          | 3.34E+11           | 3.11E+12            | 4.72E+12            |
| CED, non-renew., maintenance           |  | MJ               | 5.04E+09                                                | 5.17E+10      | 1.04E+11       | 1.01E+12        | 1.48E+12        | 4.65E+09                                                | 4.78E+10      | 9.62E+10       | 8.79E+11        | 1.33E+12        | 4.64E+09                                                | 4.76E+10          | 9.59E+10           | 8.77E+11            | 1.32E+12            |
| EPT (energy payback time)              |  | a                | 0.70                                                    | 0.75          | 0.78           | 0.78            | 0.77            | 0.64                                                    | 0.69          | 0.74           | 0.68            | 0.69            | 0.57                                                    | 0.62              | 0.66               | 0.61                | 0.62                |
|                                        |  | m                | 8.4                                                     | 8.9           | 9.4            | 9.4             | 9.2             | 7.7                                                     | 8.3           | 8.9            | 8.1             | 8.2             | 6.8                                                     | 7.4               | 8.0                | 7.3                 | 7.4                 |
| Share ST                               |  | %                | 99.76%                                                  | 96.61%        | 92.46%         | 89.31%          | 88.67%          | 99.62%                                                  | 95.26%        | 89.84%         | 88.47%          | 87.98%          | 99.52%                                                  | 94.43%            | 88.21%             | 86.65%              | 86.10%              |
| Share Lines_to_storage                 |  | %                | 0.00%                                                   | 0.00%         | 0.00%          | 0.00%           | 0.00%           | 0.00%                                                   | 0.00%         | 0.00%          | 0.00%           | 0.00%           | 0.00%                                                   | 0.00%             | 0.00%              | 0.00%               | 0.00%               |
| Share Storage                          |  | %                | 0.24%                                                   | 0.23%         | 0.17%          | 0.14%           | 0.18%           | 0.38%                                                   | 0.41%         | 0.23%          | 0.35%           | 0.35%           | 0.48%                                                   | 0.52%             | 0.29%              | 0.43%               | 0.43%               |
| Share Transmission lines               |  | %                | 0.00%                                                   | 3.16%         | 7.37%          | 10.56%          | 11.15%          | 0.00%                                                   | 4.33%         | 9.93%          | 11.19%          | 11.67%          | 0.00%                                                   | 5.05%             | 11.49%             | 12.92%              | 13.46%              |



## Peak-load, phtovoltaics

Data in this area is being imported FROM Umberto.

Data in this area is being imported TO Umberto.

Data in this area refers TO another excel-sheet in this file.

Data in this area is being referred FROM another excel-sheet in this file.

Input data refer to DLR 2004

|                             |     | state-of-the-art                                    |                |                 |                 | 2020/2030                                           |                |                 |                 | 2030 dynamic                                        |                    |                     |                     |
|-----------------------------|-----|-----------------------------------------------------|----------------|-----------------|-----------------|-----------------------------------------------------|----------------|-----------------|-----------------|-----------------------------------------------------|--------------------|---------------------|---------------------|
| Peakload                    | GW  | 5                                                   | 10             | 100             | 150             | 5                                                   | 10             | 100             | 150             | 5                                                   | 10                 | 100                 | 150                 |
| El. delivered to the grid   | TWh | 43.8                                                | 87.6           | 876             | 1314            | 43.8                                                | 87.6           | 876             | 1314            | 43.8                                                | 87.6               | 876                 | 1314                |
|                             | MJ  | 1.58E+11                                            | 3.15E+11       | 3.15E+12        | 4.73E+12        | 1.58E+11                                            | 3.15E+11       | 3.15E+12        | 4.73E+12        | 1.58E+11                                            | 3.15E+11           | 3.15E+12            | 4.73E+12            |
| Identification code         |     | Peak_PV_S_5GW                                       | Peak_PV_S_10GW | Peak_PV_S_100GW | Peak_PV_S_150GW | Peak_PV_F_5GW                                       | Peak_PV_F_10GW | Peak_PV_F_100GW | Peak_PV_F_150GW | Peak_PV_F_5GW_dyn                                   | Peak_PV_F_10GW_dyn | Peak_PV_F_100GW_dyn | Peak_PV_F_150GW_dyn |
| <b>PV</b>                   |     |                                                     |                |                 |                 |                                                     |                |                 |                 |                                                     |                    |                     |                     |
| PV_Capacity                 | GW  | 39                                                  | 77             | 829             | 1,243           | 33                                                  | 67             | 704             | 1,056           | 33                                                  | 67                 | 704                 | 1,056               |
| PV_Cap_Umberto (share!)     | GW  | 0.1                                                 | 0.1            | 0.1             | 0.1             | 0.1                                                 | 0.1            | 0.1             | 0.1             | 0.1                                                 | 0.1                | 0.1                 | 0.1                 |
| PV_Generation               | TWh | 100.19                                              | 196.35         | 2,202.92        | 3,302.33        | 84.95                                               | 174.05         | 1,881.92        | 2,822.87        | 84.95                                               | 174.05             | 1,881.92            | 2,822.87            |
| ...for export               | TWh | 80.97                                               | 159.87         | 1,721.17        | 2,581           | 68.51                                               | 139.11         | 1,461.65        | 2,192           | 68.51                                               | 139.11             | 1,461.65            | 2,192               |
| ...for excess               | TWh | 19.22                                               | 36.48          | 481.75          | 721.61          | 16.44                                               | 34.94          | 420.27          | 630.40          | 16.44                                               | 34.94              | 420.27              | 630.40              |
| eta_module_PV               | %   | 14.0                                                | 14.0           | 14.0            | 14.0            | 15.0                                                | 15.0           | 15.0            | 15.0            | 15.0                                                | 15.0               | 15.0                | 15.0                |
| PV_Lifetime                 | a   | 25                                                  | 25             | 25              | 25              | 25                                                  | 25             | 25              | 25              | 25                                                  | 25                 | 25                  | 25                  |
| eta_module_PV model         | %   | 13                                                  | 13             | 13              | 13              | 9                                                   | 9              | 9               | 9               | 9                                                   | 9                  | 9                   | 9                   |
| PV_Lifetime model           | a   | 25                                                  | 25             | 25              | 25              | 20                                                  | 20             | 20              | 20              | 20                                                  | 20                 | 20                  | 20                  |
| CED, non-renewable (share!) | MJ  |                                                     |                |                 |                 |                                                     |                |                 |                 |                                                     |                    |                     |                     |
| CED in system lifetime      | MJ  |                                                     |                |                 |                 |                                                     |                |                 |                 |                                                     |                    |                     |                     |
| CED, non-renewable          | MJ  | 1.23E+12                                            | 2.42E+12       | 2.60E+13        | 3.91E+13        | 2.95E+11                                            | 5.99E+11       | 6.30E+12        | 9.45E+12        | 2.24E+11                                            | 4.56E+11           | 4.79E+12            | 7.18E+12            |
| Lines to storage (HVAC)     |     | Values linearly extrapolated from base PV           |                |                 |                 | Values linearly extrapolated from base PV           |                |                 |                 | Values linearly extrapolated from base PV           |                    |                     |                     |
| Stor_distance_HVAC_10GW     | km  | 350                                                 | 350            | 350             | 350             | 350                                                 | 350            | 350             | 350             | 350                                                 | 350                | 350                 | 350                 |
| eta_stor_distance           | %   | 98.5                                                | 98.5           | 98.5            | 98.5            | 98.5                                                | 98.5           | 98.5            | 98.5            | 98.5                                                | 98.5               | 98.5                | 98.5                |
| CED, non-renewable          | MJ  | 8.39E+08                                            | 8.39E+08       | 8.39E+08        | 8.39E+08        | 8.39E+08                                            | 8.39E+08       | 8.39E+08        | 8.39E+08        | 5.00E+08                                            | 5.00E+08           | 5.00E+08            | 5.00E+08            |
| Hydro pump storage          |     |                                                     |                |                 |                 | no changes compared with "state-of-the-art"         |                |                 |                 |                                                     |                    |                     |                     |
| Stor_Capacity               | GW  | 28.68                                               | 56.55          | 613.27          | 919.5           | 25.26                                               | 51.36          | 542.53          | 813.79          | 25.26                                               | 51.36              | 542.53              | 813.79              |
| Stor_output                 | TWh | 8.27E+01                                            | 1.59E+02       | 1.96E+03        | 2.93E+03        | 9.96E+01                                            | 2.11E+02       | 2.51E+03        | 3.77E+03        | 9.96E+01                                            | 2.11E+02           | 2.51E+03            | 3.77E+03            |
| eta_stor                    | %   | 75.00%                                              | 75.00%         | 75.00%          | 75.00%          | 85.00%                                              | 85.00%         | 85.00%          | 85.00%          | 85.00%                                              | 85.00%             | 85.00%              | 85.00%              |
| Stor_Lifetime               | a   | 40                                                  | 40             | 40              | 40              | 40                                                  | 40             | 40              | 40              | 40                                                  | 40                 | 40                  | 40                  |
| CED, non-renewable          | MJ  | 2.78E+09                                            | 5.35E+09       | 6.59E+10        | 9.87E+10        | 3.35E+09                                            | 7.10E+09       | 8.44E+10        | 1.27E+11        | 2.73E+09                                            | 5.78E+09           | 6.88E+10            | 1.03E+11            |
| Transmission lines (HVDC)   |     | Values linearly extrapolated from base load ST      |                |                 |                 | Values linearly extrapolated from base load ST      |                |                 |                 | Values linearly extrapolated from base load ST      |                    |                     |                     |
| Trans_distance              | km  | 14,600                                              | 29,100         | 290,700         | 436,000         | 20,000                                              | 20,500         | 205,200         | 307,800         | 20,000                                              | 20,500             | 205,200             | 307,800             |
| eta_trans_HVDC              | %   | 82.00%                                              | 82.00%         | 82.00%          | 82.00%          | 86.00%                                              | 86.00%         | 86.00%          | 86.00%          | 86.00%                                              | 86.00%             | 86.00%              | 86.00%              |
| HVDC_load                   | GW  | 5.0                                                 | 5.0            | 5.0             | 5.0             | 6.5                                                 | 6.5            | 6.5             | 6.5             | 6.5                                                 | 6.5                | 6.5                 | 6.5                 |
| HVDC stations               |     | 3                                                   | 5              | 52              | 77              | 2                                                   | 4              | 37              | 55              | 2                                                   | 4                  | 37                  | 55                  |
| Trans_Lifetime              | a   | 50                                                  | 50             | 50              | 50              | 50                                                  | 50             | 50              | 50              | 50                                                  | 50                 | 50                  | 50                  |
| CED, non-renewable          | MJ  | 2.42E+10                                            | 4.93E+10       | 4.90E+11        | 7.95E+11        | 3.11E+10                                            | 4.36E+10       | 4.74E+11        | 7.39E+11        | 2.35E+10                                            | 3.29E+10           | 3.58E+11            | 5.58E+11            |
| Source                      |     | Tab. 111-113 Tab. 116-118 Tab. 121-123 Tab. 126-128 |                |                 |                 | Tab. 121-133 Tab. 136-138 Tab. 141-143 Tab. 146-148 |                |                 |                 | Tab. 121-133 Tab. 136-138 Tab. 141-143 Tab. 146-148 |                    |                     |                     |
| CED, non-renewable          | MJ  | 1.25E+12                                            | 2.48E+12       | 2.66E+13        | 4.00E+13        | 3.31E+11                                            | 6.51E+11       | 6.86E+12        | 1.03E+13        | 2.51E+11                                            | 4.95E+11           | 5.21E+12            | 7.84E+12            |
| EPT (energy payback time)   | m   | 3.18E+00                                            | 3.14E+00       | 3.37E+00        | 3.38E+00        | 8.39E-01                                            | 8.26E-01       | 8.70E-01        | 8.72E-01        | 8.38E-01                                            | 8.25E-01           | 8.70E-01            | 8.72E-01            |
|                             |     | 38.2                                                | 37.7           | 40.5            | 40.5            | 10.1                                                | 9.9            | 10.4            | 10.5            | 10.1                                                | 9.9                | 10.4                | 10.5                |
| Share PV                    | %   | 97.78%                                              | 97.76%         | 97.91%          | 97.76%          | 89.31%                                              | 92.08%         | 91.85%          | 91.60%          | 89.34%                                              | 92.07%             | 91.80%              | 91.56%              |
| Share Lines_to_storage      | %   | 0.07%                                               | 0.03%          | 0.00%           | 0.00%           | 0.25%                                               | 0.13%          | 0.01%           | 0.01%           | 0.20%                                               | 0.10%              | 0.01%               | 0.01%               |
| Share Storage               | %   | 0.22%                                               | 0.22%          | 0.25%           | 0.25%           | 1.01%                                               | 1.09%          | 1.23%           | 1.23%           | 1.09%                                               | 1.17%              | 1.32%               | 1.32%               |
| Share Transmission lines    | %   | 1.93%                                               | 1.99%          | 1.84%           | 1.99%           | 9.42%                                               | 6.70%          | 6.91%           | 7.16%           | 9.37%                                               | 6.66%              | 6.87%               | 7.12%               |

## Peak-load, solar thermal

Data in this area is being imported FROM Umberto.

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Data in this area refers TO another excel-sheet in this file.

Data in this area is being referred FROM another excel-sheet in this file.

Input data refer to DLR 2004

|                                    |                  | state-of-the-art                                        |                |                 |                 | 2020/2030                                               |                |                 |                 | 2030 dynamic                                            |                    |                     |                     |
|------------------------------------|------------------|---------------------------------------------------------|----------------|-----------------|-----------------|---------------------------------------------------------|----------------|-----------------|-----------------|---------------------------------------------------------|--------------------|---------------------|---------------------|
| Peakload                           | GW               | 5                                                       | 10             | 100             | 150             | 5                                                       | 10             | 100             | 150             | 5                                                       | 10                 | 100                 | 150                 |
| El. delivered to the grid          | TWh              | 43.8                                                    | 87.6           | 876             | 1314            | 43.8                                                    | 87.6           | 876             | 1314            | 43.8                                                    | 87.6               | 876                 | 1314                |
| Identification code                | MJ               | 1.58E+11                                                | 3.15E+11       | 3.15E+12        | 4.73E+12        | 1.58E+11                                                | 3.15E+11       | 3.15E+12        | 4.73E+12        | 1.58E+11                                                | 3.15E+11           | 3.15E+12            | 4.73E+12            |
|                                    |                  | Peak_ST_S_5GW                                           | Peak_ST_S_10GW | Peak_ST_S_100GW | Peak_ST_S_150GW | Peak_ST_F_5GW                                           | Peak_ST_F_10GW | Peak_ST_F_100GW | Peak_ST_F_150GW | Peak_ST_F_5GW_dyn                                       | Peak_ST_F_10GW_dyn | Peak_ST_F_100GW_dyn | Peak_ST_F_150GW_dyn |
| <b>ST</b>                          |                  |                                                         |                |                 |                 |                                                         |                |                 |                 |                                                         |                    |                     |                     |
| ST_Capacity                        | GW               | 11.2                                                    | 22.3           | 223.6           | 335.5           | 10.83                                                   | 21.55          | 216.03          | 324.1           | 10.83                                                   | 21.55              | 216.03              | 324.1               |
| ST_Cap_Umberto (share!)            | GW               | 0.1                                                     | 0.1            | 0.1             | 0.1             | 0.1                                                     | 0.1            | 0.1             | 0.1             | 0.1                                                     | 0.1                | 0.1                 | 0.1                 |
| ST_field size                      | m2               | 220,000,000                                             | 437,600,000    | 4,387,800,000   | 6,582,700,000   | 201,900,000                                             | 401,600,000    | 4,027,000,000   | 6,041,600,000   | 201,900,000                                             | 401,600,000        | 4,027,000,000       | 6,041,600,000       |
| ST_field size_Umberto (share!)     | m2               | 1,964,286                                               | 1,962,332      | 1,962,343       | 1,962,057       | 1,864,266                                               | 1,863,573      | 1,864,093       | 1,864,116       | 1,864,266                                               | 1,863,573          | 1,864,093           | 1,864,116           |
| ST_thermal_stor                    | GW <sub>th</sub> | 435.9                                                   | 867.3          | 8,696           | 13,046          | 400.11                                                  | 796.01         | 7,981           | 11,974          | 400.11                                                  | 796.01             | 7,981               | 11,974              |
| ST_thermal_stor                    | h                | 24.0                                                    | 24.0           | 24.0            | 24.0            | 24.0                                                    | 24.0           | 24.0            | 24.0            | 24.0                                                    | 24.0               | 24.0                | 24.0                |
| ST_thermal_stor_Umberto (share!)   | GW <sub>th</sub> | 0.162                                                   | 0.162          | 0.162           | 0.162           | 0.154                                                   | 0.154          | 0.154           | 0.154           | 0.154                                                   | 0.154              | 0.154               | 0.154               |
| ST_Generation                      | TWh              | 80.96                                                   | 161.07         | 1,538.31        | 2,422.90        | 78.22                                                   | 155.91         | 1,600.18        | 2,340.76        | 78.22                                                   | 155.91             | 1,600.18            | 2,340.76            |
| ...for export                      | TWh              | 51.94                                                   | 103.33         | 1,036.00        | 1,554.40        | 50.18                                                   | 99.83          | 1,000.90        | 1,501.70        | 50.18                                                   | 99.83              | 1,000.90            | 1,501.70            |
| ...for excess                      | TWh              | 29.02                                                   | 57.74          | 502.31          | 868.50          | 28.04                                                   | 56.08          | 599.28          | 839.06          | 28.04                                                   | 56.08              | 599.28              | 839.06              |
| eta_PB                             | %                | 33.00%                                                  | 33.00%         | 33.00%          | 33.00%          | 33.00%                                                  | 33.00%         | 33.00%          | 33.00%          | 33.00%                                                  | 33.00%             | 33.00%              | 33.00%              |
| eta_ST                             | %                | 37.60%                                                  | 37.60%         | 37.60%          | 37.60%          | 39.40%                                                  | 39.40%         | 39.40%          | 39.40%          | 39.40%                                                  | 39.40%             | 39.40%              | 39.40%              |
| ST_DNI_Umberto                     | kWh/m2           | 2,966                                                   | 2,966          | 2,825           | 2,966           | 2,980                                                   | 2,986          | 3,056           | 2,980           | 2,980                                                   | 2,986              | 3,056               | 2,980               |
| ST_Lifetime                        | a                | 30                                                      | 30             | 30              | 30              | 30                                                      | 30             | 30              | 30              | 30                                                      | 30                 | 30                  | 30                  |
| CED, non-renew. (share!) , constr. | MJ               | 2.52E+09                                                |                |                 |                 | 2.40E+09                                                |                |                 |                 | 1.49E+09                                                |                    |                     |                     |
| CED, non-renew. (share!) , maint.  | MJ               | 5.55E+08                                                |                |                 |                 | 5.27E+08                                                |                |                 |                 | 5.25E+08                                                |                    |                     |                     |
| CED, non-renewable, constructio    | MJ               | 2.82E+11                                                | 5.62E+11       | 5.64E+12        | 8.46E+12        | 2.60E+11                                                | 5.17E+11       | 5.18E+12        | 7.78E+12        | 1.62E+11                                                | 3.22E+11           | 3.23E+12            | 4.84E+12            |
| CED, non-renewable, maintenanc     | MJ               | 6.22E+10                                                | 1.24E+11       | 1.24E+12        | 1.86E+12        | 5.70E+10                                                | 1.14E+11       | 1.14E+12        | 1.71E+12        | 5.69E+10                                                | 1.13E+11           | 1.13E+12            | 1.70E+12            |
| Lines to storage (HVAC)            |                  | Values linearly extrapolated from 0,1 GW to ST_capacity |                |                 |                 | Values linearly extrapolated from 0,1 GW to ST_capacity |                |                 |                 | Values linearly extrapolated from 0,1 GW to ST_capacity |                    |                     |                     |
| Stor_distance_HVAC_10GW            | km               |                                                         |                |                 |                 |                                                         |                |                 |                 |                                                         |                    |                     |                     |
| eta_stor_distance                  | %                |                                                         |                |                 |                 |                                                         |                |                 |                 |                                                         |                    |                     |                     |
| CED, non-renewable                 | MJ               |                                                         |                |                 |                 |                                                         |                |                 |                 |                                                         |                    |                     |                     |
| <b>Hydro pump storage</b>          |                  |                                                         |                |                 |                 |                                                         |                |                 |                 |                                                         |                    |                     |                     |
| Stor_Capacity                      | GW               |                                                         |                |                 |                 |                                                         |                |                 |                 |                                                         |                    |                     |                     |
| Stor_output                        | TWh              |                                                         |                |                 |                 |                                                         |                |                 |                 |                                                         |                    |                     |                     |
| eta_stor                           | %                |                                                         |                |                 |                 |                                                         |                |                 |                 |                                                         |                    |                     |                     |
| Stor_Lifetime                      | a                |                                                         |                |                 |                 |                                                         |                |                 |                 |                                                         |                    |                     |                     |
| CED, non-renewable                 | MJ               |                                                         |                |                 |                 |                                                         |                |                 |                 |                                                         |                    |                     |                     |
| <b>Transmission lines (HVDC)</b>   |                  |                                                         |                |                 |                 |                                                         |                |                 |                 |                                                         |                    |                     |                     |
| Trans_distance_HVDC                | km               | 14,600                                                  | 29,100         | 290,700         | 436,000         | 20,000                                                  | 20,500         | 205,200         | 307,800         | 20,000                                                  | 20,500             | 205,200             | 307,800             |
| eta_trans_HVDC                     | %                | 82.00%                                                  | 82.00%         | 82.00%          | 82.00%          | 86.00%                                                  | 86.00%         | 86.00%          | 86.00%          | 86.00%                                                  | 86.00%             | 86.00%              | 86.00%              |
| HVDC_load                          | GW               | 5.0                                                     | 5.0            | 5.0             | 5.0             | 6.5                                                     | 6.5            | 6.5             | 6.5             | 6.5                                                     | 6.5                | 6.5                 | 6.5                 |
| HVDC stations                      |                  | 3                                                       | 5              | 52              | 77              | 2                                                       | 4              | 37              | 55              | 2                                                       | 4                  | 37                  | 55                  |
| Trans_Lifetime                     | a                | 50                                                      | 50             | 50              | 50              | 50                                                      | 50             | 50              | 25              | 50                                                      | 50                 | 50                  | 25                  |
| CED, non-renewable                 | MJ               | 5.90E+10                                                | 1.18E+11       | 1.17E+12        | 1.76E+12        | 1.04E+11                                                | 1.06E+11       | 1.06E+12        | 1.60E+12        | 7.84E+10                                                | 8.04E+10           | 8.05E+11            | 1.21E+12            |
| Source                             |                  | Tab. 114-115 Tab. 119-120 Tab. 121-125 Tab. 129-130     |                |                 |                 | Tab. 134-135 Tab. 139-140 Tab. 144-145 Tab. 149-150     |                |                 |                 | Tab. 134-135 Tab. 139-140 Tab. 144-145 Tab. 149-150     |                    |                     |                     |
| CED, non-renew., construction      | MJ               | 3.41E+11                                                | 6.80E+11       | 6.81E+12        | 1.02E+13        | 3.64E+11                                                | 6.24E+11       | 6.25E+12        | 9.38E+12        | 2.40E+11                                                | 4.02E+11           | 4.03E+12            | 6.05E+12            |
| CED, non-renew., maintenance       | MJ               | 6.22E+10                                                | 1.24E+11       | 1.24E+12        | 1.86E+12        | 5.70E+10                                                | 1.14E+11       | 1.14E+12        | 1.71E+12        | 5.69E+10                                                | 1.13E+11           | 1.13E+12            | 1.70E+12            |
| EPT (energy payback time)          | a                | 1.03                                                    | 1.02           | 1.03            | 1.03            | 1.08                                                    | 0.92           | 0.93            | 0.93            | 0.99                                                    | 0.83               | 0.83                | 0.83                |
|                                    | m                | 12.3                                                    | 12.3           | 12.3            | 12.3            | 12.9                                                    | 11.1           | 11.1            | 11.1            | 11.9                                                    | 9.9                | 10.0                | 10.0                |
| Share ST                           | %                | 82.72%                                                  | 82.71%         | 82.76%          | 82.77%          | 71.46%                                                  | 82.94%         | 82.96%          | 82.96%          | 67.34%                                                  | 80.01%             | 80.04%              | 80.04%              |
| Share Lines_to_storage             | %                | 0.00%                                                   | 0.00%          | 0.00%           | 0.00%           | 0.00%                                                   | 0.00%          | 0.00%           | 0.00%           | 0.00%                                                   | 0.00%              | 0.00%               | 0.00%               |
| Share Storage                      | %                | 0.00%                                                   | 0.00%          | 0.00%           | 0.00%           | 0.00%                                                   | 0.00%          | 0.00%           | 0.00%           | 0.00%                                                   | 0.00%              | 0.00%               | 0.00%               |
| Share Transmission lines           | %                | 17.28%                                                  | 17.29%         | 17.24%          | 17.23%          | 28.54%                                                  | 17.06%         | 17.04%          | 17.04%          | 32.66%                                                  | 19.99%             | 19.96%              | 19.96%              |

## 8.3.2 Input Data for the Space Systems

Data in this area is being imported FROM Umberto.  
 Data in this area is being imported TO Umberto.  
 Data in this area refers TO another excel-sheet in this file.  
 Data in this area is being referred FROM another excel-sheet in this file.

Input data refer to EADS 2004c

|                                   |     | 2020/2030        |                  |                  |                  |                   | 2030 dynamic         |                      |                      |                      |                       |
|-----------------------------------|-----|------------------|------------------|------------------|------------------|-------------------|----------------------|----------------------|----------------------|----------------------|-----------------------|
| Baseload                          | GW  | 10               | 25               | 50               | 75               | 100               | 10                   | 25                   | 50                   | 75                   | 100                   |
| El. delivered to the grid         | TWh | 87.6             | 219              | 438              | 657              | 876               | 87.6                 | 219                  | 438                  | 657                  | 876                   |
| Identification code               | MJ  | 3.15E+11         | 7.88E+11         | 1.58E+12         | 2.37E+12         | 3.15E+12          | 3.15E+11             | 7.88E+11             | 1.58E+12             | 2.37E+12             | 3.15E+12              |
|                                   |     | Base_Comb_F_10GW | Base_Comb_F_25GW | Base_Comb_F_50GW | Base_Comb_F_75GW | Base_Comb_F_100GW | Base_Comb_F_10GW_dyn | Base_Comb_F_25GW_dyn | Base_Comb_F_50GW_dyn | Base_Comb_F_75GW_dyn | Base_Comb_F_100GW_dyn |
| SPS                               |     |                  |                  |                  |                  |                   |                      |                      |                      |                      |                       |
| Number of SPS-stations            |     | 1                | 3                | 6                | 9                | 12                | 1                    | 3                    | 6                    | 9                    | 12                    |
| CED, non-renewable (1 SPS)        | MJ  | 1.53E+11         | 4.60E+11         | 9.21E+11         | 1.38E+12         | 1.84E+12          | 1.07E+11             | 3.21E+11             | 6.43E+11             | 9.64E+11             | 1.29E+12              |
| CED, non-renewable, construction  | MJ  | 1.30E+11         | 3.90E+11         | 7.80E+11         | 1.17E+12         | 1.56E+12          | 9.08E+10             | 2.72E+11             | 5.45E+11             | 8.17E+11             | 1.09E+12              |
| CED, non-renewable, maintenance   | MJ  | 2.34E+10         | 7.02E+10         | 1.40E+11         | 2.11E+11         | 2.81E+11          | 1.63E+10             | 4.90E+10             | 9.81E+10             | 1.47E+11             | 1.96E+11              |
| PV                                |     |                  |                  |                  |                  |                   |                      |                      |                      |                      |                       |
| Number of ground PV               |     | 1                | 1                | 2                | 3                | 4                 | 1                    | 1                    | 2                    | 3                    | 4                     |
| PV_Capacity_daylight              | GW  | 11.2             | 11.2             | 22.4             | 33.6             | 44.8              | 11.2                 | 11.2                 | 22.4                 | 33.6                 | 44.8                  |
| PV_Capacity_laser                 | GW  | 0                | 0                | 0                | 0                | 0                 | 0                    | 0                    | 0                    | 0                    | 0                     |
| PV_Capacity_total                 | GW  | 11.2             | 11.2             | 22.4             | 33.6             | 44.8              | 11.2                 | 11.2                 | 22.4                 | 33.6                 | 44.8                  |
| PV_Cap_Umberto (share!)           | GW  | 0.1              | 0.1              | 0.1              | 0.1              | 0.1               | 0.1                  | 0.1                  | 0.1                  | 0.1                  | 0.1                   |
| eta_module_PV_daylight            | %   | 15.0             | 15.0             | 15.0             | 15.0             | 15.0              | 15.0                 | 15.0                 | 15.0                 | 15.0                 | 15.0                  |
| eta_module_PV_laser               | %   | 50.0             | 50.0             | 50.0             | 50.0             | 50.0              | 50.0                 | 50.0                 | 50.0                 | 50.0                 | 50.0                  |
| PV_Lifetime                       | a   | 25               | 25               | 25               | 25               | 25                | 25                   | 25                   | 25                   | 25                   | 25                    |
| eta_module_PV model               | %   | 9                | 9                | 9                | 9                | 9                 | 9                    | 9                    | 9                    | 9                    | 9                     |
| PV_Lifetime model                 | a   | 20               | 20               | 20               | 20               | 20                | 20                   | 20                   | 20                   | 20                   | 20                    |
| CED, non-renewable                | MJ  | 1.11E+11         | 1.11E+11         | 2.23E+11         | 3.34E+11         | 4.45E+11          | 8.46E+10             | 8.46E+10             | 1.69E+11             | 2.54E+11             | 3.38E+11              |
| CED, non-renewable, change of eta | MJ  | 6.68E+10         | 6.68E+10         | 1.34E+11         | 2.00E+11         | 2.67E+11          | 5.08E+10             | 5.08E+10             | 1.02E+11             | 1.52E+11             | 2.03E+11              |
| CED in system lifetime            | MJ  | 1.00E+11         | 1.00E+11         | 2.00E+11         | 3.01E+11         | 4.01E+11          | 7.61E+10             | 7.61E+10             | 1.52E+11             | 2.28E+11             | 3.05E+11              |
| Lines_to_storage (HVAC)           |     |                  |                  |                  |                  |                   |                      |                      |                      |                      |                       |
| Stor_distance_HVAC_10GW           | km  |                  |                  |                  |                  |                   |                      |                      |                      |                      |                       |
| eta_stor_distance                 | %   |                  |                  |                  |                  |                   |                      |                      |                      |                      |                       |
| CED, non-renewable                | MJ  |                  |                  |                  |                  |                   |                      |                      |                      |                      |                       |
| Hydro pump storage                |     |                  |                  |                  |                  |                   |                      |                      |                      |                      |                       |
| Stor_Capacity                     | GW  |                  |                  |                  |                  |                   |                      |                      |                      |                      |                       |
| Stor_output                       | TWh | 2.00E-01         | 5.00E-01         | 1.00E+00         | 1.50E+00         | 2.00E+00          | 2.00E-01             | 5.00E-01             | 1.00E+00             | 1.50E+00             | 2.00E+00              |
| eta_stor                          | %   | 85.00%           | 85.00%           | 85.00%           | 85.00%           | 85.00%            | 85.00%               | 85.00%               | 85.00%               | 85.00%               | 85.00%                |
| Stor_Lifetime                     | a   | 40               | 40               | 40               | 40               | 40                | 40                   | 40                   | 40                   | 40                   | 40                    |
| CED, non-renewable                | MJ  | 6.73E+06         | 1.68E+07         | 3.36E+07         | 5.05E+07         | 6.73E+07          | 5.48E+06             | 1.37E+07             | 2.74E+07             | 4.11E+07             | 5.48E+07              |
| Transmission lines (HVDC)         |     |                  |                  |                  |                  |                   |                      |                      |                      |                      |                       |
| Trans_distance_HVDC               | km  | 10,000           | 25,000           | 50,000           | 75,000           | 100,000           | 10,000               | 25,000               | 50,000               | 75,000               | 100,000               |
| eta_trans_HVDC                    | %   | 90.00%           | 90.00%           | 90.00%           | 90.00%           | 90.00%            | 90.00%               | 90.00%               | 90.00%               | 90.00%               | 90.00%                |
| HVDC_Load                         | GW  | 6.5              | 6.5              | 6.5              | 6.5              | 6.5               | 6.5                  | 6.5                  | 6.5                  | 6.5                  | 6.5                   |
| HVDC stations                     |     | 2                |                  |                  |                  |                   | 2                    |                      |                      |                      |                       |
| Trans_Lifetime                    | a   | 50               | 50               | 50               | 50               | 50                | 50                   | 50                   | 50                   | 50                   | 50                    |
| CED, non-renewable                | MJ  | 5.19E+10         | 1.30E+11         | 2.60E+11         | 3.89E+11         | 5.19E+11          | 3.92E+10             | 9.80E+10             | 1.96E+11             | 2.94E+11             | 3.92E+11              |
| Source                            |     | EADS             | EADS             | EADS             | EADS             | EADS              | EADS                 | EADS                 | EADS                 | EADS                 | EADS                  |
| CED, non-renew., construction     | MJ  | 2.82E+11         | 6.20E+11         | 1.24E+12         | 1.86E+12         | 2.48E+12          | 2.06E+11             | 4.47E+11             | 8.93E+11             | 1.34E+12             | 1.79E+12              |
| CED, non-renew., maintenance      | MJ  | 2.34E+10         | 7.02E+10         | 1.40E+11         | 2.11E+11         | 2.81E+11          | 1.63E+10             | 4.90E+10             | 9.81E+10             | 1.47E+11             | 1.96E+11              |
| EPT (energy payback time)         | a   | 0.37             | 0.33             | 0.33             | 0.33             | 0.33              | 0.35                 | 0.31                 | 0.31                 | 0.31                 | 0.31                  |
| Share SPS                         | %   | 4.4              | 3.9              | 3.9              | 3.9              | 3.9               | 4.2                  | 3.7                  | 3.7                  | 3.7                  | 3.7                   |
| Share PV                          | %   | 46.09%           | 62.92%           | 62.92%           | 62.92%           | 62.92%            | 44.04%               | 60.99%               | 60.99%               | 60.99%               | 60.99%                |
| Share Lines_to_storage            | %   | 35.51%           | 16.16%           | 16.16%           | 16.16%           | 16.16%            | 36.93%               | 17.05%               | 17.05%               | 17.05%               | 17.05%                |
| Share Storage                     | %   | 0.000%           | 0.000%           | 0.000%           | 0.000%           | 0.000%            | 0.000%               | 0.000%               | 0.000%               | 0.000%               | 0.000%                |
| Share Transmission lines          | %   | 0.002%           | 0.003%           | 0.003%           | 0.003%           | 0.003%            | 0.003%               | 0.003%               | 0.003%               | 0.003%               | 0.003%                |
|                                   | %   | 18.39%           | 20.92%           | 20.92%           | 20.92%           | 20.92%            | 19.02%               | 21.95%               | 21.95%               | 21.95%               | 21.95%                |