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PETER GLASER LECTURE:
SPACE AND A SUSTAINABLE 21^{ST} CENTURY ENERGY SYSTEM

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ABSTRACT

Independent of the current high oil and gas prices, that might eventually fall again, with world population increasing toward 9 billion, and living standards of large parts of the world increasing accordingly energy demand will increase rapidly, straining the entire supply chain from exploration to refining. In addition, environmental problems associated with our current fossil fuel based energy system gain importance and might well prove one of the most difficult problems to solve in this century. Energy supply far in excess of the human metabolic energy is at the very basis for sustaining a human population size in excess of its Earth natural "carrying capacity", estimated for humans to be in the order of 3 persons per square kilometre. The 19th century has brought the most dramatic change in the energy system fuelling human activities after the discovery of fire: from an almost entirely biomass burning society at its beginning to a society obtaining almost 80% of its primary energy from fossil fuel (coal) burning at its end in western economies. The 20th century has seen two further radical changes: the introduction of two other forms of fossil fuel, oil and gas, enabling the emerging transport industry and the introduction of nuclear power, both together reducing the share of coal to less than 20% at the end of the century.

An energy system based on burning of fossil fuels with lifecycles of thousands and millions of years is inherently unsustainable. The accompanying environmental aspects (CO_2 emissions), issues of health in agglomerations and loss of biosphere, not to mention the threat of climate change, indicate the need for another substantial change in our energy system for the 21st century. The alternative offered by technologies such as CO_2 sequestration or nuclear power generation, literally "sweep the problem under the carpet" by leaving a legacy of buried CO_2 or of millions of cubic meters of radioactive waste to future generations. We are still in the fossil fuel age, but first signs are pointing towards its end. Space might in three respects play an important role for the new, still to be defined energy age. The present paper focuses on three aspects: energy sources as the first transformation toward a sustainable society, and the heritage of energy systems for space as precursors for terrestrial systems, the possible role of space assets as a tool for energy management in a sustainable society, and finally energy from space via space based power generation plants. A look at the next steps to prepare for such a future role concludes the paper.

INTRODUCTION

Humanity has been relying on a sustainable energy system based on the use of renewable bio-mass burning until about the early 19th century, when the (discovery and) massive introduction of denser forms of stored solar energy in form of relatively cheap and abundant coal, oil and gas enabled the phenomenal human progress rate of the last 200 years, accompanied by an exponential increase of the total world population.

While for a long time, fossil fuels seemed to exist in infinitely larger reserves than humanity could ever need, the rapid and ever increasing power consumption (increase by a factor of 16 during the 20th century compared to a population increase by only a factor 4) cannot be sustained forever. Put another way, we burn each day resources that nature took 10,000 days to create.

Furthermore, the environmental effects of the massive use of fossil fuels are only now becoming clearly recognised and have become the strongest incentive for a substantial change of the energy system to power the 21st century. Pre-industrial levels of CO_2 were steady at 280 ppm, they are now at 380 ppm and there's a consensus that constraining emissions to stay under the limit of 500 ppm can be achieved, while continuing on the current path may lead to levels (800 ppm) which may trigger catastrophic climate change within this century.

Energy supply far in excess of the human metabolic energy is at the very basis for sustaining a human population size in excess of its Earth natural "carrying capacity", estimated for humans to be in the order to 3 persons per square kilometre.[5] While the_metabolic "power need" of a human being is around a 100 W, the

US pro-capita use is 10,000W, with a worldwide average of 2,200W pro-capita.

Because of all the above factors, sustainability is the greatest technical and societal challenge to confront us this century. As space engineers, it is natural to ask ourselves what role can space systems play in facilitating this transformation.

One can take comfort in the fact that since energy systems developed for space systems need to be inherently sustainable and fossil fuel free, these have been the precursors for most renewable (with the exception of wind and biomass) terrestrial energy systems for the 21st century.
Space technologies and overall energy management in space systems will most likely still stimulate research and development for terrestrial equipment.

Beyond this, telecommunications that are pushing information rather than mass are also an area where space systems are likely to contribute. Finally, the gradual introduction of renewable energy sources is likely to require new energy generation and distribution management systems, including in addition to monitoring also production forecasting and real-time distribution system adaptation. The first section will deal with the potential role of space technology in the near term drive toward sustainability.

The second section goes one step further, assessing whether and under what conditions space solar power plants will be able to compete with terrestrial solar power plants to actually supply to the terrestrial power grid by generating power in space and converting and transmitting it to Earth-bound receiver sites possibly identical to already existing terrestrial solar power plants.

The conclusion will indicate what the authors believe are near term actions to move forward in making SPS a realistic option as an energy source over the next few decades.

SPACE IN THE SERVICE OF ENERGY SUSTAINABILITY

Currently, the average share of wind and solar generated electricity in IEA member[1] countries is only 0.4%. High growth rates in some countries and fast technical evolution will continue to increase their share over-proportionally (e.g. 60% average wind generation growth in Germany between 1990 and 2001).[1][3][6]
The extrapolation of these average growth rates will lead to electricity generation shares of renewable and decentralised power generation stations that will

- change the way the electricity grid functions;
- introduce the “consumer-producer” and therefore stop the current clear separation between large centralised units on the production edge and small distributed units at the consumer edge;
- enhance the already ongoing separation of production units and the grid ownership/management;
- require novel grid management approaches.

In this section, we will briefly address the later point: the requirement for novel grid management approaches. Traditional grid management has to take into account essentially three parameters: (1) the location, capacity and reaction times of production units, (2) the location and capacity of the distribution system and (3) the location and expected power requirements of the consumer units.

The grid system evolved in Europe from an initially locally managed grid, with consumer units essentially surrounding central power generation plants, to a regional system, before becoming a system based on national grids with only limited inter-national electricity exchange capacity. Europe is currently in the process of slowly “Europeanising” its grid with inter-national current exchange becoming more and more important. The basic grid management system has however remained the same since its basic structure as outlined above has not changed. The increase of the share of renewable energy sources will however change this system in order to remain efficient. The introduction of many small-scale consumer-producers, in form of roof-top PV, farm-based biomass stations and wind power plants requires in addition to forecast of expected consumer demand, the reliable forecast of the expected production capacity and its location.

While the traditional production capacity is centrally controllable according to expected power demands, a system with a significant share of power generated by weather-dependent renewable power stations (wind, solar) will need to include production forecasting dependent on weather forecasting when determining the production capacity at any moment. Otherwise, the share of renewable power stations would needed to be backed up at any moment by additional generation capacity on standby.

Space assets are the first choice when monitoring and forecasting weather. Weather monitoring satellites are constantly improving their spatial and temporal resolution and weather models are improving fast to achieve more and more reliability in forecasting.

A grid as described above will require real-time weather monitoring and forecasting. Space assets however are able to go substantially beyond the simple provision of weather monitoring images: With small position determination receiver and satellite based communication terminals integrated into the distributed renewable power plants (wind turbines, PV fields or roof-top PVs etc), the control nodes of the power distribution grid and into potentially additional networks of small weather monitoring stations, real-

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[1] International Energy Agency [1]

time information on the current actual generation capacity and exact location would be fed into a space-based system, which in turn would not only monitor the grid system and forecast production levels and locations but it would also be well suited to monitor and control the distribution system in an optimised way.

The comparison of the actual production levels at any moment and any location of plants with the weather data at that location and moment would in addition enable the system to learn and constantly adapt its forecasts. It would immediately detect and be able to report anomalies, recognise patterns and intelligently anticipate behaviours (from anomalies in single production units to the avoidance of blackouts and their propagation). A system level assessment including a better definition of the system requirements and trade-offs with ground-based alternatives is currently under way within the General Studies Programme of the European Space Agency.

Other possibilities in this sense are offered for instance by monitoring of snow and ice depth on glaciers, providing an indication of hydroelectric seasonal reserves. GIS data is being exploited to find the best sites for wind turbines, etc. The ESA Earth Observation programme is already preparing some of these applications in pre-operational trials.

Other applications are likely to emerge along with the transformation of industries toward a sustainable model. Synergy in the use of heat, where one company's waste becomes another one's input, may profit from Earth Observation satellites data, etc.

Local production of goods, reducing the need for energy hungry shipping, will require enhanced transcontinental communication means, again a domain of excellence for satellites. The remaining transport will profit from more economic route planning, thanks to better digital elevation maps, better knowledge of oceanic currents, wind patterns and weather, Global Navigation Satellite Systems and enhanced Air Traffic Management through satellite systems.

Finally, space is today the largest user of hydrogen for transportation purposes, leads in development of high performance solar cells and high power storage systems. Space technology is therefore also an important knowledge base for the sustainable energy sources development. However, space industries themselves will need to review their processes in order to become environmentally sustainable, from energy usage to production of toxic waste.

Over the next few decades, as the transformation of our society in a sustainable one becomes widespread, the above-mentioned ideas may provide a useful role for space systems.

This transformation will primarily concern the reduction of fossil fuels as a primary energy source, to be progressively substituted by less polluting, renewable sources. However, some of the solutions put forward today as long term solutions are not inherently sustainable. Nuclear power generates vast amounts of non recyclable nuclear waste, which must be stored underground for safe disposal and may take centuries to reduce its radioactivity, not to mention its chemical toxicity. Burying CO_2 also does not guarantee that it will not seep out in the future, presenting future generation with an even more daunting challenge than the one we face today.

Considering that today we use about 14 TW of energy (of which about 85% comes from fossil fuels), and that the Earth intercepts about 170,000 TW of power from the sun, the case for solar thermal, PV power generation plants and their distributed use in the residential and industrial sector seems very clear. Would it make economic sense to expand this capability to Space Solar Power Satellites, as envisaged in the 60's by P. Glaser? Would such systems make energy sense? i.e. would they produce more energy during their lifetime than that required for fielding them?

SOLAR POWER FROM SPACE

When taking the above outlined reasoning one step further, one would not only (1) use space systems for the monitoring, forecasting and control/management of terrestrial electricity/hydrogen grids with a significant contribution share of renewable power sources and (2) regard space systems as precursor models and test beds for the development of sustainable terrestrial energy systems, but use space assets to actually provide power to Earth-bound receiver sites and thus contribute to a sustainable, clean energy system not relying on fossil fuels.[9]

Solar power plants on Earth and in space are among the promising long-term energy options, principally able to cover humanities ever increasing energy need in a sustainable way free of greenhouse gas emission. Half a decade after the first use of photovoltaic cells in space and benefiting from research and development for space, terrestrial solar power is one of the fastest growing energy sectors with high growth rates sustained over more than a decade (especially in Europe) and very promising forecasts. [1][3][6][12][21]

While the first photovoltaic cells for space delivered just a few mW of electric power, modern telecom satellites operate at about 20 kW_e and the panels of the International Space Station ISS have been planned to provide around 100 kW_e in its final configuration. Extrapolating this trend and adding the ever-increasing array efficiency and kW/kg ratio leads directly to visionary concepts for solar power satellites, producing solar-generated power to be transmitted to the Earth surface. Compared to terrestrial solar plants, the advantages of permanent illumination by the sun (limited storage needs), no weather and climate effects have to be weighted against space transportation costs, in space operations, safety aspects and conversion losses in the wireless power transmission system.

All studies concluded the principal technical feasibility of the concepts and gradually improved their power to mass ratio. [9][10] [16][17][18][24] No substantial development efforts were undertaken however since with current technology space generated electricity costs would still be too high, upfront costs prohibitive and the launcher/space sector not mature enough to reduce €/kg to orbit costs by the required order of magnitude.

In the past, space concepts were mainly compared to traditional energy systems. Based on this background, the Advanced Concepts Team (ACT) at the European Space Agency started a three-phased programme in 2003.[7][8] The first phase of the programme, the Validation Phase, focused on a comparison of space solar power plants with comparable terrestrial solutions on the one hand and the assessment of the potential of SPS for space exploration and space application on the other.[26][27]

Comparison of space and terrestrial solar power plants - results

The results have been published and presented in detail. [25][26][28] Under the set boundary conditions of (1) a restriction to the larger European context (not taking into consideration global systems), (2) realistic technology maturity projections for the 2020/2030 timeframe and (3) the inclusion of only solar options for terrestrial systems, solar power plants in space are competitive with solar plants on Earth only above certain minimum relatively high power levels.

Energy storage systems play a crucial role in this comparison. The availability of local hydro-storage capacity reduces the terrestrial solar generated energy costs significantly compared to the use of hydrogen, which in turn is in principle location independent.

Taking into account the level reached by terrestrial solar power plants, the current activities and plans for new plants in the south European sun belt (essentially Spain and Italy) and the fast increase of the total installed PV capacity, relatively large-scale terrestrial solar plants will already feed electricity into the energy grid when space solar plants will still be in early programme phases.

As first steps, it seems therefore interesting to first investigate the potential of integrating space solar power plants into terrestrial ones. Results obtained during the first phase of the European SPS Programme Plan indicate that under the taken assumptions, the addition of space plants to terrestrial ones does not substantially alter the achieved electricity generation costs. (Figure 1) [7][11][31]

Table 1: Comparison: peak-load scenarios
Space (RF power transmission) – terrestrial (solar tower) ; values for pumped hydro-storage in brackets

Total power supplied GWe	**Concept**	**Generation cost** €/kWh	**Required launch cost** (€/kg)
0.5	terrestrial	10.6 (10.2)	
	space	441	-
5	terrestrial	7.6 (6.6)	
	space	36	-
10	terrestrial	5.3 (4.0)	
	space	19	-
50	terrestrial	1.09 (0.7)	
	space	0.871	155 (-)
100	terrestrial	0.673 (0.48)	
	space	0.246 (0.245)	958 (540)
150	terrestrial	0.532 (0.280)	
	space	0.131 (0.130)	1615 (605)

Table 2 Comparison: base-load supply scenarios
microwave wireless power transmission based space systems and distributed terrestrial solar tower plants. (values for pumped hydro-storage option scenarios in brackets)

Total Power supplied GWe	**Concept**	**electricity generation cost** €/kWh	**required launch costs** €/kg (LEO)
0.5	terrestrial	0.09 (0.06)	
	space	0.28 (0.28)	-
5	terrestrial	0.08 (0.05)	
	space	0.04 (0.04)	750 (200)
10	terrestrial	0.08 (0.05)	
	space	0.05 (0.05)	620 (90)
50	terrestrial	0.08 (0.05)	
	space	0.04 (0.03)	770 (270)
100	terrestrial	0.08 (0.05)	
	space	0.03 (0.03)	770 (250)
500	terrestrial	0.08 (0.05)	
	space	0.04 (0.04)	670 (210)

In the mentioned case, terrestrial solar power plant located in an non-populated and currently not otherwise used terrain in north-African Egypt as well as a system of distributed relatively small solar tower plants in the south-European sunbelt have been studied as reference terrestrial systems for all considered power levels (0.5 to 500 GW$_e$) and for peak load as well as base-load power supply. For detailed information on the chosen solar terrestrial plant concepts we refer to [7][11][18][22][23][29][30][31].

In all cases, the plants were designed to supply power according to realistic projections of European power load curves based on current measured demand profiles and consumption increase forecasts.

Base-load Power Supply

In the case of base-load scenarios, terrestrial solar tower plants with local hydrogen storage capacities promise electricity generation costs between 9 and 7.6 € cent/kWh for the smallest (500 MW$_e$) and the largest (500 GW$_e$) plants respectively. Solar power satellites are not competitive with the lower scenarios even with free earth to space transportation (zero launch costs).

For the 5 GW_e and higher scenarios, launch costs between 620 and 770 €/kg are required for SPS to be competitive with terrestrial plants. In case local pumped hydrostorage facilities are available, the required launch costs would be significantly lower with roughly one third of these values. (Table 2)

Combined space-terrestrial solar plant systems

For the combined system (the integration of space and terrestrial solar plants) the range of (terrestrial) technology options imposed the reduction of the analysis to distinctive scenarios. Within each scenario, the levelised electricity costs were calculated for the entire range: from power from space only to no additional power from space. The design of the ground receiver changes in type, spacing and inclination depending whether it should be optimized as ground system for the space segment or as pure terrestrial solar plant.

The four scenarios assessed in detail and referred to for comparison in Figure 1 were

- S-1: central PV receiver optimized for laser beam, additional PV optimized for solar irradiation; pumped hydroelectric storage;
- S-2: central PV receiver optimized for laser beam, additional PV optimized for solar irradiation; hydrogen pressure vessel storage;
- S-3: entire PV receiver optimized for laser beam; pumped hydroelectric storage;
- S-4: entire PV receiver optimized for solar irradiation; pumped hydroelectric storage.

The results of the combination in terms of levelised electricity generation costs (LEC) for the entire range from all-space to no-space extremes for each of the four scenarios are displayed in Figure 1. It can be seen that given the uncertainty inherent in 20-year forecasts, the LEC for the different scenarios (except the one optimized for converting only direct solar irradiation; S-1) are very close to each other and not changing dramatically by changing the percentage of space to ground supplies.

Non base-load Power Supply

For non-base-load scenarios, solar tower plants with local hydrogen storage capacities have generation costs between 10 €/kWh for the smallest scenarios to 53 € cent/kWh for the largest (150 GW_e) plants. Solar power satellites reach potentially competitive electricity generation costs above relatively large plant sizes of about 50 GW_e.

For the 50 GW_e and higher scenarios, launch costs between 155 and 1615 €/kg would be required for SPS to reach a competitive level to terrestrial plants. In case local pumped hydro storage facilities are available, the required launch costs would be lowered by about a factor two.

Table 3: Comparison of energy payback times for space and terrestrial solar power plants (SOT 1: South European Solar Tower Scenario, SOT 2: North African Solar Trough plant scenario, PV: North African Solar Photovoltaic plant scenario)

Total Power Supply GWe	**Concept**	**energy payback time** Months
0.5	SOT1 (H2)	8.40
	SOT2 (pumped)	7.70
	PV (pumped)	8.20
	SPS laser	-
	SPS µ-wave	24.00
5	SOT1 (H2)	8.40
	SOT2 (pumped)	8.30
	PV (pumped)	9.20
	SPS laser	-
	SPS µ-wave	4.80
10	SOT1 (H2)	8.40
	SOT2 (pumped)	8.90
	PV (pumped)	8.20
	SPS laser	4.40
	SPS µ-wave	4.80
100	SOT1 (H2)	8.40
	SOT2 (pumped)	8.10
	PV (pumped)	8.30
	SPS laser	3.90
	SPS µ-wave	4.80
150	SOT1 (H2)	8.40
	SOT2 (pumped)	8.20
	PV (pumped)	8.50
	SPS laser	-
	SPS µ-wave	4.80

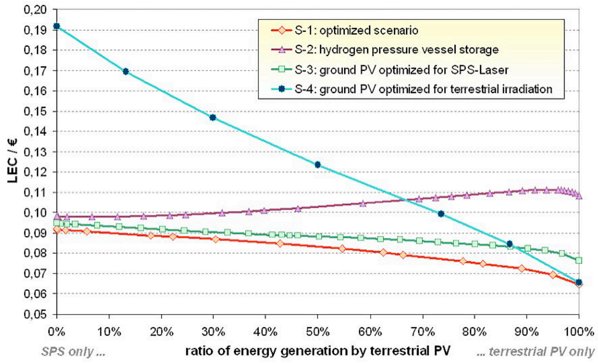

Figure 1: Comparison of integrated space-terrestrial solar power plants in terms of LEC[2] in €

Treatment of Launch Costs

Launch costs are the single most important parameter in assessing the economic viability of solar power satellites. The assumption of fixed launch costs would

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[2] LEC: levelised electricity costs

predetermine the outcome of system comparison studies.

As a consequence, launch costs were treated as open parameters for the present assessments between boundaries given by the current launch cost as upper and the fuel costs as lower limit.

In order to overcome the "chicken-egg" problem of: the launch frequency required by the construction of SPS reduces the launch costs to values required for the economic construction and operation of SPS, a "learning curve approach" was used. Starting from current launch costs, a 20% reduction was assumed by each doubling of the total launch mass. (progress rate of 0.8)

In a first step, space and terrestrial plants were compared while excluding launch costs. This comparison and the total cost difference were then taken to determine the maximum allowed launch costs for the space scenario in order to be competitive with terrestrial plants.

In a third step, the progress rate was used to determine the reduction of the launch costs due to the launches of SPS components for all scenarios. This value was then compared to the required value to become competitive for a certain scenario as determined in step two. The approach did not take into account multiplication factors due to the opening of additional markets created by lower launch costs.

Comparison of Energy payback times

Given the high uncertainty inherent to some of the system aspects, a comparison of space and terrestrial plants based on only physics parameters was done. Contrary to past work, energy values were calculated without using an assumed €-Joule connection, but taking as a basis energy intensities for subsystem components and materials (specialised databases).

For all regarded cases, the energy payback times for space and terrestrial solar power plants were lower or equal to one year. For the Egypt-based terrestrial system, the energy payback times seem to be slightly higher than for the distributed system in the European solar belt. In both cases, from a purely energetic point, solar power satellites promise a slightly shorter energy payback time that are however of course within the general error margins applicable for such forecasts.

CONCLUSIONS

The fossil fuel based energy system that powered the 19th and 20th century is likely required to be replaced by a more sustainable one based on a combination of nuclear and renewable energy. While at the beginning, networks of small distributed power stations (wind and solar essentially) are expected to contribute significantly, at a later stage, solar power transmitted from space to large terrestrial solar power stations seem possible and attractive. At the same time, space activities are expected to mature and gradually grow into new markets, which may decrease currently prohibitively high launch costs.

The paper has presented three specific cases where space might contribute substantially to the energy sector and thus to one of the major open questions for the 21st century: the intelligent and real-time management of energy (electricity/hydrogen) grids fed by renewable power stations at substantial levels, the precursor role of energy systems developed for space and the longer-term option of adding solar power generated in space to a terrestrial energy grid. For the later case, the results of a comparison of space-based and terrestrial based solar power plants with technology expected to be mature in the 2020/2030 timeframe were compared in terms of levelised electricity generation costs, energy payback times and their potential integration.

Achievement of such capabilities, even a few decades from today, requires technological advancement that we must pursue now. Various technologies are involved: from higher performance PV arrays, both in terms of W/g and efficiency; to wireless power transmission (WPT) systems, and especially lasers, which seem to become ever more capable. The most appropriate architecture for the system will probably need another "fresh look" in a matter of few years, to take into account a number of ideas generated in the last few years. Last but not least, technological demonstrations, even at low scale, will allow the dual role of practical test beds and public communication items. A tower or a blimp, which can test different solutions for energy conversion and WPT, can also raise public awareness of SPS potential (the inherent scaling laws of SPS are unfavourable to space-to-Earth SPS system demonstrations). In this sense, the recent Furoshiki experiment, which tested on a sounding rocket wireless power transmission and robotic deployment of large structures, is a very welcome start: low cost, high technological challenge, excellent international cooperation between Japan and Europe and, perhaps most important, key student participation.

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