



The Role of Power from Space within the Global Economy

~ ~ ~

Solar Power Satellites – An European Perspective – Start-up Meeting
ESA Headquarters, 28 August 2002

Dr Marco C Bernasconi
MCB Consultants/ Andromeda srl

PPH-02-034

1.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

OUTLINE



- Human industrial power needs into the XXI century
- Thermal burden, and other environmental issues
- Needs for development of power-from-space systems
- Ways towards demonstrators

2.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

XXI CENTURY HUMAN INDUSTRIAL POWER NEEDS -- POWER SPECIFIC LEVELS



- A historical correlation exists between population density (persons/km²) and specific power used (kW/person)
- Industrial societies have a specific power level of 10 kW/person (typical)
- Energy availability is the most efficient parameter for wealth generation
- Electrification reduces the direct consumption (say, 3 kW/person), but not the environmental burden (as long as power generation occurs with the biosphere)
- Required equivalent power level:
 - 150 TW (Earth-generated)
 - 30 TW (space-generated)

3.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

METABOLIC ENERGY – EQUIVALENT FRACTIONS



Use / Commodity	Net Global Need	Primary-Production Equivalent	Fraction of Global Production
Vegetable food	1.04 TW	2.08 TW	2.04%
Herbivore animal food	0.208 TW	2.60 TW	2.55%
Carnivore animal food	0.052 TW	5.91 TW	5.79%
Total	1.3 TW	10.59 TW	10.38%

4.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

IRRELEVANCE OF BIOMASS FOR POWER



- Fuel wood usage shows large geographic variations
- In industrialized countries, it amounts to a small fraction (< 10%) of total wood use
- Fuel use of biomass (other than from real wastes) not to be recommended:
 - largely insufficient (industrial power needs exceed total biospheric mass yield)
 - food & fibres production already imply large impact on biosphere
 - chemical complexity of biomass makes it better suited as processing feed stock

5.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

NOVEL NEEDS: POWER SUBSIDIES FOR FOOD PRODUCTION



- During the XX century, harvest yields have grown by a factor of 5
- The "energy subsidy" input to support farming has multiplied by 50
- Today, the energy subsidy corresponds to 1/3 of the produce's energy content
- Following the historical trend, it could surpass twice the energy in the harvest by 2025
- Required total energy subsidy: 1 - 3 TW

6.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics



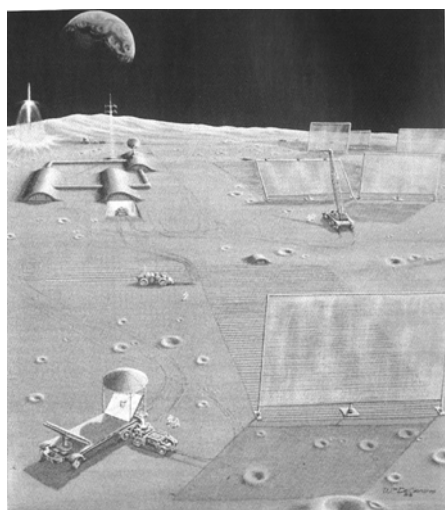
NEED: WEALTH GENERATION

- The products to fulfill those needs are not "give-aways," some form of handout, at the expense of "society"
- While being produced, they will concur to generate wealth
- By 2100, the gross world product would be
 - \$200 trillion, for an average level equivalent to today's industrialized countries'
 - \$2000 trillions per year, with an added 2.3% growth rate
- Assuming an average capital input of 2.13% (historical US-industry data) and an energy input of 2.84%, a Cobb-Douglas production model yields
 - 232% increase in production by 2030 (with doubling work force)
 - a further increase by a factor 5 by 2100 (with constant work force)
 - proportionally scaled, this corresponds to a 2100 gross world product of \$240 trillion

7.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

ECONOMIC CONTRIBUTIONS OF POWER FROM SPACE



Lunar Power System (LPS) (Criswell & Waldron, 1991)

- \$100 billion cumulative R&D investments in the first five years
- \$500 billion investments for development, production and start of operations
- revenues surpass \$1600 billion 15 years into the project
- \$14 trillion/a revenue of full system
- \$74 trillion "excess returns" (Waltz & Thompson, 1993)

8.00.280.802
Power From Space

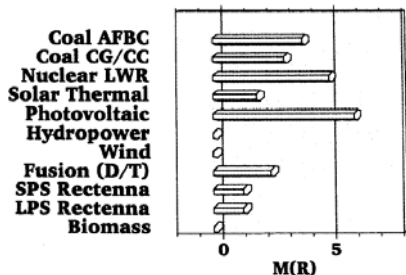
Software, Real-Time Systems, Methodologies - Technologies for Astronautics

THERMAL BURDEN FROM POWER GENERATION

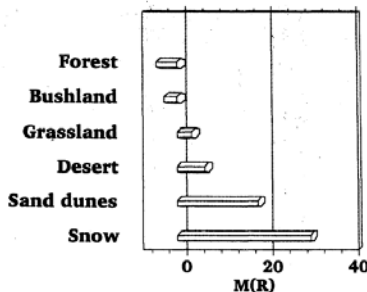


- Thermal burden: total additional power (averaged energy released over time) liberated within the biosphere to provide for human needs
- All power-generation approaches (but possibly for hydro) have positive “thermal burden multipliers”, but space-based generation’s is smallest.

On the Basis of the Capital Energy Inputs



For Ground Photovoltaics on Various Surfaces



9.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

THERMAL BURDEN DATA



	M(R)	Th. Burden [TW]	Veg. Flow [%]	Area [Mm2]
Coal AFBC	3.895	272.65	50.77	0.0007
Coal CG/CC	3.095	216.65	40.34	0.0007
Nuclear LWR	5.055	353.85	65.89	0.0007
Solar Thermal	1.888	132.16	24.61	2.5455
Photovoltaic	6.149	430.43	80.15	5.0725
Hydropower	-0.013	-0.91	-0.17	0.0700
Wind	-0.025	-1.75	-0.33	0.0700
Fusion (D/T)	2.487	174.09	32.42	0.0007
SPS Rectenna	1.283	89.81	16.72	0.7609
LPS Rectenna	1.282	89.74	16.71	0.3804
Biomass	0.000	0.00	0.00	20.5882

On the basis of the capital energy inputs (from Bernasconi, 1994)

10.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

THE SPACE OPTION CONCEPT



- The Space Option bases on the use of extraterrestrial resources, applying them for use on Earth, on a significant extent, i.e. to provide for a conspicuous fraction of the needs of ground based societies.
- The concept was introduced as a major element of the rationale that ought to inform and justify public space activities
- Nonetheless, no agency is addressing the opportunities for space development and colonization.
 - ESA LSPC advisory body included consideration of space resources among its recommendations:

"Intelligent use of space resources might be the missing link between our basic drive for prosperity and wealth, and the imperative of protecting Earth from irreversible devastation."
 - Japan's METI has planned to install a 1-GW solar power station by 2040.

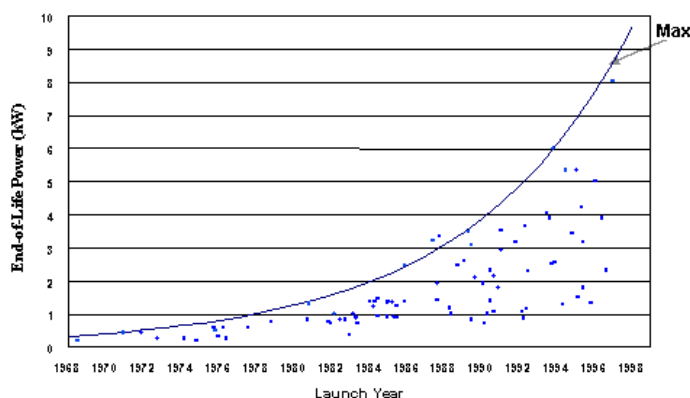
11.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

"NATURAL" DEVELOPMENT TIME-SCALE



- The maximum power installed on communications satellites has grown exponentially for the last 30-odd years.
- The trend projects a power greater than 38 kW by 2010
- The 5-GW level is reached in 2113!
- Thus, SPS demand a significant acceleration of "historical" trends (Even METI's target needs a 1000x acceleration).



12.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

NASA'S SOLAR POWER SATELLITE



The NASA "Fresh Look" SPS uses inflatable tori with a flexible Fresnel lens concentrating the solar flux onto (high efficiency) PV cells.

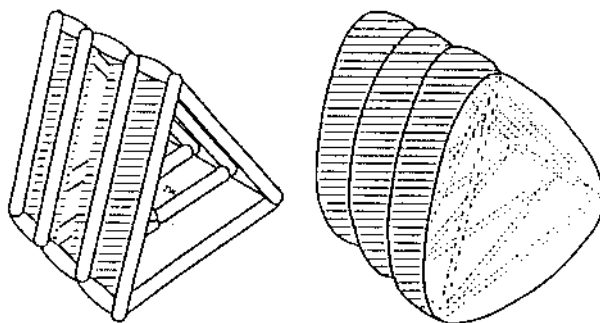
BUT:

- Inflatable structures are a mid-term help only
- Inflatables & high-efficiency PV cells are terrestrial exports
- Concentrators contribute little over modest silicon TFPV

13.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

SPS2000 STRUCTURAL CONCEPTS



Prof Natori has discussed different structural concept for the 1-MW "SPS-2000" ISAS power-from-space demonstrator using gossamer (inflatable) elements

14.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

POWER-FROM-SPACE DEVELOPMENT NEEDS



- To fully succeed, power from space must be part of an extraterrestrial resources utilization project
- Real, operational SPS will be manufactured from lunar materials
- Public-choice theory shows how governments have little incentive to truly address major issues
- That the Agencies see themselves as the “gatekeepers to space” explains the glacial progress during the last 20 years for
 - “returning” to the Moon
 - developing extraterrestrial production systems
 - providing technologies like: space installation of large structures, low-cost power generation, and microwave power transmission
- “Soft” needs would seem to encompass:
 - cooperative networking
 - benevolent insider support, e.g. to progress with flight experiments
 - creative morphing and combining of actual technical developments

15.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

FIRST STEPS TOWARDS DEMONSTRATORS

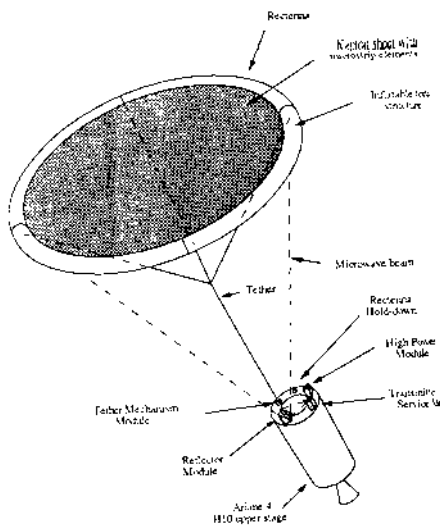


- Modest steps will occupy us for quite a few years
- Technology work to cover:
 - gossamer structures for the large apertures in collector & transmitter
 - lower-cost, low-mass solar cells (TFPV)
 - lower-cost, low-mass, large-area transmitters
 - low-cost rectenna elements
 - multifunctional space elements
- Possible demonstrators – all using gossamer structures
 - microwave power transmission in space
 - 500-kW power-from-space satellite
 - integrated technology experimental spacecraft
- “Commercial” studies concerning e.g.:
 - initial & interim markets for SPS technologies & mw power transmission
 - terrestrial & space niches & market mechanisms
 - opening geolunar space for commerce

16.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

POWER TRANSMISSION EXPERIMENT

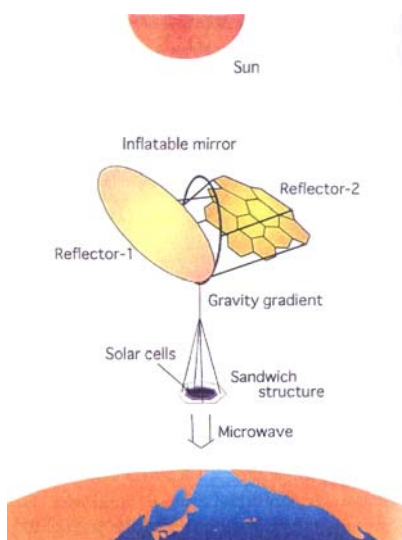


- Planar Instrument Carrier (PICs) are toroidal support using chemically rigidized expandable structures.
- A 1992 study proposed a wireless power transmission experiment using a PIC-based ISRS rectenna structure (Eurosace image).

17.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

LATE 1990s UPDATED JAPANESE SPS CONCEPT



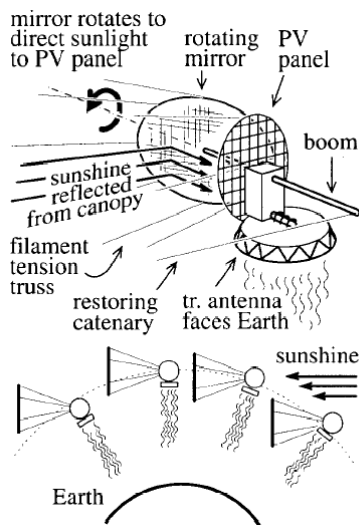
An updated, slimmed down, gravity gradient solar power satellite concept with an inflatable admittance mirror, to eliminate the power bus (Kaya, 1998).

A CR of about 10 was used to reduce the solar cell area.

18.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

THE "SOLAR PARACHUTE" POWER SATELLITE



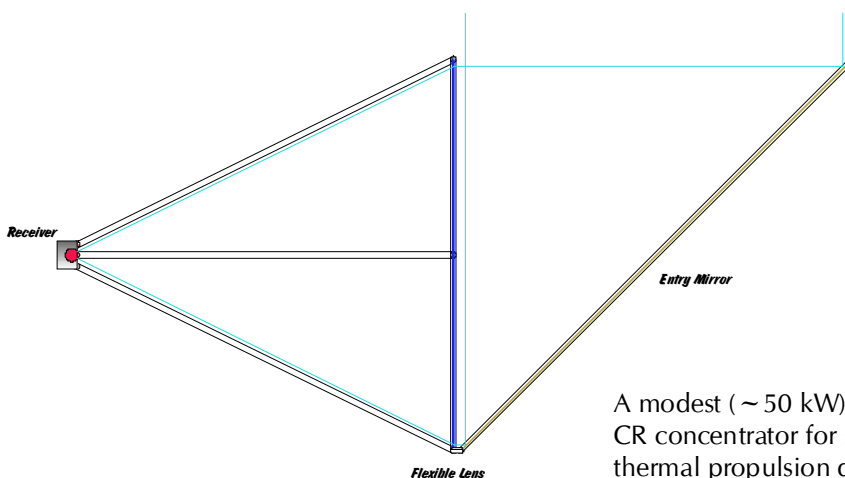
A gossamer concept for a solar power satellite discussed by Greschik & Mikulas (2000).

A concentrating/ admitting mirror assembly tracks the Sun and feeds the transmission antenna

19.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

FRESNEL-LENS COLLECTOR FOR STP



A modest (~ 50 kW), but higher CR concentrator for solar-thermal propulsion discussed under the STOTS Study

20.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics

CONCLUSIONS



- Access to extraterrestrial resources is an ethical imperative
- Power generation receives a high priority from physical and economic facts
- Progress remains extremely modest, but
 - power from space never required major progress in technology
 - incremental products' development and demonstration steps can serve to improve the economics of a solution
 - major need is on acquiring business models
- Demonstration of various functions all seem to require a strong injection of gossamer/ "inflatable" structures technology, that deserves basic support
- Other technological areas for near-term support:
 - thin-film photovoltaics, flexible, large-area transmit arrays
 - low-cost rectenna elements, multifunctional space elements
- Commercialization networks and studies of fundamental significance

21.00.280.802
Power From Space

Software, Real-Time Systems, Methodologies - Technologies for Astronautics