EARTH & SPACE-BASED POWER GENERATION SYSTEMS
A COMPARISON STUDY

– EXECUTIVE SUMMARY –

A Study for ESA Advanced Concepts Team

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0 SUMMARY

This study was conducted by L-B-Systemtechnik (Munich / Germany) subcontracting Space Future Consulting (Northampton / United Kingdom), TNC Consulting AG (Erlenbach / Switzerland), the Institute of Microtechnology of the University of Neuchâtel (Neuchâtel / Switzerland) and MCB Consultants (Dietikon / Switzerland) for ESA (Advanced Concepts Team).

The **objective** of the study is to comparatively assess the economic viability, energy investment, risk and reliability issues of broad-scale introduction of terrestrial and space based solar power systems for a European power supply in 2030 at various scenario power levels.

Under the scenario conditions given, **key findings** of the study are:

- Scenario design in terms of base load and non-base load cases is only suited to gain principle knowledge about both terrestrial and space-based solar power system architectures. They do not reflect today's and even less the future complexity of successively liberalized energy markets which comprise a mix of primary energy sources, ownership models and further energy markets, such as transporation fuel.
- The comparative cost, risk and reliability discussions and evaluations are based on highly asymmetrical input data due to different magnitudes of practical experiences.
- For base load scenarios solar thermal power plants which are mainly installed in Europe are chosen as terrestrial reference system. For non-base load scenarios terrestrial photovoltaic systems are selected as terrestrial reference system and installed on a decentralized basis preferably in the European sunbelt. For energy storage two options are considered: the hydrogen pathway due to its flexibility and the pumped hydro storage for economic reasons yet at limited availability.
- For cost calculation of space systems launch costs are treated as open parameter. Launch cost targets for space systems are calculated to be competitive with terrestrial scenarios. Assumptions for launch cost targets base on today’s launch technology with learning effect of 20% cost reduction with each doubling of cumulated mass transportation into orbit. New reusable launch vehicle could lead to higher cost reductions and to lower allowable final launch cost targets.

- Results for base load scenarios: solar power satellite (SPS) systems may be competitive to terrestrial solar thermal power generation (SOT) systems for 50, 100 and 500 GW_e scenarios with the hydrogen storage option. SPS systems are not competitive to terrestrial SOT systems with the pumped hydro storage option, where those are feasible.
- Results for non-base load scenarios: SPS systems may be competitive to terrestrial photovoltaic systems for 100 and 150 GW_e scenarios with the hydrogen storage and for 150 GW_e scenario with the pumped hydro storage option, where those are feasible.
- The combination of space and terrestrial solar power systems in order to substitute terrestrial storage requirements do not lead to synergies and cost advantages unless power is also delivered outside Europe or hydrogen fuel production for transportation sector is considered. The technical feasibility of co-siting rectennae with solar thermal power plants has to be doubted in principle due to partial shading of direct sun light. If technical obstacles are overcome, co-siting with large-scale terrestrial photovoltaic power plants would reduce the required land area if centralized terrestrial PV plants were assumed.
- Potential synergy effects may be expected due to common technology basis (i.e. photovoltaic cells). Further synergies beyond the scope of this study are given due to the production of hydrogen fuel but also due to network synergies for SPS systems where non-base load power could be provided on a competitive basis.
- Different financing, operation and market requirements are attributed with the technologies assessed. Space-based solar power systems and solar thermal power plants exclusively serve the wholesale market at potentially high equivalent full load hours. Terrestrial photovoltaic systems are additionally suited to supply private customer directly in the framework of highly decentralized power generation systems. With terrestrial based solar power systems in general, investment costs may be split among a great number of different investors. Space-based solar power systems are likely to require a joint European effort for realization which is embedded in a strong international legal framework.
- Energy payback times of terrestrial and space systems are between 0.4 to 4.4 years (mostly 0.4 - 0.7 years according to DIN) and is thus in any case way below the operational lifetimes. Energy effort of space systems is dominated by the production of space transportation vehicle whereas the energy effort of terrestrial-based solar power systems is dominated by storage requirements.

- Launch targets in order to be competitive with the terrestrial reference system: space transportation infrastructure has to be developed for average payload transportation costs between 1,551 EUR/kg$_{payload}$ and 91 EUR/kg$_{palyoad}$ with final launch costs between 1,060 EUR/kg$_{payload}$ and 17 EUR/kg$_{payload}$. It has to be noted that some 90% of overall transportation capacity has to be launched at the final target launch costs. Launch is critical to the overall economic viability of space-based solar power systems.
- Risk and reliability: central issues which are in the focus of discussion are: Can the technical and cost targets be achieved (especially space transportation), system failure tolerance as well as vulnerability towards sabotage/terror attacks, environmental and health risks, interference due to microwave power transmission, geo-political implications.
- Key issues for further research of the viability of space-based solar power systems are among others: Detailed technical (inter alia FMEA), economic (investors, cash-flow etc.) and environmental analysis of most promising system architectures and high-capacity space-transportation vehicles; validation experiments and demonstration eventually resulting in a pilot plant; Development of a 'SPS business plan' in collaboration with major stakeholders; Assessment of public acceptance and geo-political implications of a broad-scale introduction of terrestrial and space-based solar power supply.

Driving forces: the look for a sustainable energy supply

Growth of mankind with cumulative degree of industrialization will desirably lead to increased living standards for the whole population on earth. Affiliated to this goal of social development is a minimum level of energy consumption. Today, some two billion people have no access to electricity. These people do not directly participate in the consumption of energy. In 2030, eight billion people – or even more – will be part of mankind. Eight million individuals with a basic right on housing, food, education, health care, job etc. In opposite to mankind’s desired goal of social development stands the limitation of natural resources and especially the limited ability of the atmosphere to absorb increasing amounts of greenhouse gases. Thus the increasing need for energy can not be met by fossil sources for the compelling need of climate protection.

Greenhouse warming is a quite well accepted fact within the scientific community and the knowledge is broadly accepted and published. Not so with the fact that world oil production is close to its maximum and possibly will decline already in the very near future. More and more it becomes obvious that today’s oil and gas dominated economy is at its highest levels. This is associated with growing energy dependence on a decreasing number of countries that own the resources. Thus the look for future energy sources has to meet two demands: it must be greenhouse gas neutral and it has to be available even in a long perspective.

Study approach and methodology

The goal of this study is to comparatively assess terrestrial and space based solar power systems regarding three result dimensions: costs, risks and reliability. The overall scope of the project was split into four work packages. In work package I and II, terrestrial and space based solar power system architectures are designed and assessed with the objective of base load and non-base load power generation. In work package III synergies between terrestrial and space solar power systems are examined. Finally, in work package IV energy payback rates are assessed.

Definitions for work packages I and II

For a transparent comparison of space based solar power systems with terrestrial solar power systems, two basic scenario cases for base load (WP1) and non-base load (WP2) operation were considered. For base load scenarios 0.5 GW, 5 GW, 10 GW, 50 GW, 100 GW and 500 GW power levels are evaluated and for non-base load scenarios the power levels 0.5 GW, 5 GW, 10 GW, 50 GW, 100 GW and 150 GW are considered.

Base load scenario design implies very pessimistic cost figures for terrestrial solar power plants due to the required storage capacities.

Non-base load scenario design implies extremely pessimistic cost figures for space-based solar power due to the very low system utilization and geographic limitation on Europe solely. This also applies to terrestrial solar power plants, yet to a lower magnitude.

Scenario definitions for WP1 and WP2 also include the limitation to compare solar power satellites (SPS) systems solely with solar power plants. Other energy sources – such as wind, biomass or hydro power – are not considered and explicitly excluded from the comparisons. This results in higher storage requirements and costs for terrestrial scenarios due to the fact that terrestrial storage is a major cost driver.

The development and discussion of large scale space transport carriers is beyond the scope of this study. Thus, the launch costs are treated as an open parameter. All cost statements for space systems are primarily evaluated without launch costs, which are then added as a parameter.

Definitions for work package III

The aim of WP3 is to identify synergies between terrestrial and space-based solar power systems. Mutual synergies in system operation could not be identified. However, non-mutual synergies apply to space as well as terrestrial systems.

Thus, WP3 was subdivided into "synergies from terrestrial perspective" and "synergies from space perspective".

Further (non-mutual) synergies for terrestrial as well as space-based power systems are discussed though they are beyond the primary scope of the study.

Definition for work package IV

In work package IV the energy payback times of the selected concepts are determined and compared. Therefore life cycle analysis for all components, materials have been considered as well as the energy effort required for construction, installation and maintenance of the respective systems.

In contrast to the methodology of launch parameterization for the WP1 and WP2 comparison, in WP4 specific launch assumptions had to be fixed for energy related calculations. For the comparison, different launch vehicles have been considered in order to gain knowledge on the sensitivity of results which is attributed to the selection of the space vehicle.

General definitions and assumptions

Solar thermal (SOT) power technology

Four different technologies of solar thermal power plants are discussed and described for terrestrial concepts: parabolic trough, central receiver, parabolic dish and solar chimney power plants. After a detailed evaluation of the favored parabolic trough and central receiver technology, central receiver solar power plants with a gross output of 220 MW_e were selected for terrestrial base load scenarios. The plant concept inherently comprises an integrated 13 hours thermal storage for reason of economic optimization, thus resulting in 6,400 hours per year. Major cost reduction potentials of some 50% are identified for the heliostat field of the central receiver plants.

Photovoltaic (PV) technology

Various PV technologies are already on the market or have the potential to be on the market within the next decade. For all terrestrial scenarios conventional and available PV technologies have been considered. A learning curve and a resulting cost degression of 20% for each doubling in production capacity is historically proven and has been generally agreed within this study. For terrestrial WP2 'non-base load' scenarios photovoltaic (PV) systems are mainly selected due to their high modularity.

For space installations thin film technologies applying very light substrates (metal or polymer) have been considered. These technologies are still under development today; prototype cells in laboratory scale already have shown success in operation. Looking at the general timeframe when space applications might start to be installed this very efficient and light weight cell type is considered to be available for space applications. Due to their reduced mass - compared with conventional systems - very light solar plant constructions are possible especially under space conditions.

Solar power satellites (SPS)

For the space scenarios two different SPS concepts are selected from the NASA Fresh Look Study [NASA 1997]. For the smallest scenarios of 0.5 GW_e eight 'Sun Tower' in medium altitude earth orbit (MEO) are selected which are designed to provide 250 MW_e each to the grid. For all other power levels several modular 'Solar Disk' systems in geo-stationary earth orbit (GEO) are chosen and scaled for a power supply of 1 GW_e, 5 GW_e and 10 GW_e.

Power transmission from space

For space based systems power transmission via microwaves was selected analogue to the reference SPS concepts described in the NASA Fresh Look Study.

The microwave transmission system is assumed to operate at a frequency of 5.8 GHz. The power density limit at the fence of the rectenna is in general subjected to local regulations. This study is based on NASA assumptions of 1 W/m^2.

For base load and non-base load scenarios the following satellite : rectenna ratios are selected: 4:1 for 'Sun Tower in MEO' (each 250 MW_e), 1:1 and 2:1 for 'Solar Disk in GEO' (each 5 GW_e and 10 GW_e respectively). Other concepts for flexible operation of solar power satellites and rectennae, such as de-coupled operation, are additionally discussed in this study.

Rectennae are sited on-shore in zone 1 locations along the 40° latitude and if required also in zone 2 along the 45° and 50° latitude. As a first estimation rectennae sited in zone 1 are assumed to use the same sites as terrestrial SOT plants. Off-shore rectennae have been discussed but not considered for the specific scenario designs due to higher costs compared with on-shore rectennae.

Solar potentials

To derive the potentials for the supply of solar energy and the potential of space and terrestrial solar applications, so called 'sun zones' are defined. Sun zone 0 covers the countries along the Mediterranean coastal line of North Africa (Algeria, Egypt, Libya, Morocco, Tunisia). Sun zone 0 is the zone with the highest annual irradiation values. Sun zone 1 comprises the countries in the European sunbelt – these are Portugal, Spain, Italy, Greek and Turkey. Especially Turkey may provide large potentials at high solar irradiation. Sun zone 2 subsumes the compementing rest of Europe.

For the siting of terrestrial solar power plants, the overall priority is given to zone 1 areas in order to be independent from energy imports from non-European countries. For the 500 GW scenario it was selected to include North African territories.

European grid

It was assumed, that the European high voltage grid will be successively enforced due to the requirements of a step by step deregulated single European energy market and the integration of continuously rising amounts of fluctuating renewable energies (wind, PV, etc.).

10 GW_e is considered as the maximum allowable size of one power station. A single power plant with more than 10 GW electricity output is considered as a risk which is not tolerable regarding the stability of the electricity grid and the security of supply.

In the course of the study, HVDC is applied to transmit electricity from North Africa to the European countries and for large-scale power distribution within Europe. The threshold when to apply HVDC and not HVAC lines for inner-European power distribution is set to 10 GW_e per location.

Power demand

For scenario calculation, the virtual single European power demand has to be synthesized ('EUROPE-2030'). Primary data is provided by [UCTE 2003] by means of hourly load data for every third Wednesday, Saturday and Sunday of each month. These singular data are scaled up and interpolated to form a load curve which covers a whole year in hourly steps for the defined EUROPE 2030. For the calculation of the required HVDC power transmission capacities in Europe, the local power consumption is estimated and subtracted from the locally produced power. Thus, the amount of electricity which was to be transmitted via HVDC was diminished.

Energy storage

For a continuous base load power supply of 8,760 full load hours per year as well as for a system optimization for non-base load scenarios, additional electricity storage capacities are required and selected.

Various electricity storage technologies are discussed for their applicability for the scenarios, such as batteries, pumped hydro energy storage, compressed air energy storage, hydrogen storage, flywheel, supercapacitor and superconduction magnetic energy storage. Thereof, two storage options have been selected for scenarios calculation: **hydrogen storage** has been selected as energy storage because it can be stored over a very long time without further loss of energy (in contrast to batteries which have a self-discharge) and its high energy density. Flexibility is also high due to technological modularity. Hydrogen storage may be applied on a large (centralized) or a small (distributed) scale. Furthermore this energy storage technology does not require certain environmental conditions, such as geology (compressed air storage) or topology (pumped hydro storage). The 'hydrogen storage' option includes the water electrolysis for hydrogen production via electricity supplied directly by terrestrial respectively space based solar power plants, a spherical pressure vessel for hydrogen storage and a fuel cell (FC) or combined circle gas turbine (CCGT) for re-electrification of hydrogen into electricity. **Pumped hydro storage** has been selected because pumped hydro storage plants provide high full-cycle efficiencies and are already in operation for many years. The use of pumped hydro is subjected to geographical conditions. Energy storage requirements, which stem from scenario assessments are assumed to be newly built facilities. Thus, no existing pumped hydro storage capacities are considered (conservative approach).

Land use

At the first project workshop, it was jointly agreed only to take the use of land into account which is required for power transmission. The cost have been assumed fixed at 10 EUR/m^2.

Decommissioning and recycling

Decommissioning and recycling costs are not considered and are thus excluded from calculations.

Launch parameterization

Launch (i.e. space transportation) is the principal and most critical cost issue for SPS systems. It is beyond the scope of this study to discuss technological progress, launch vehicle concepts or similar. Applying a reverse calculation approach, the study solely focuses the calculation of space transportation cost targets, which would have to be realized in order to achieve economic competitiveness with the respectively terrestrial solar power generation system.

For the calculation of the learning curve average launch cost targets as well as assumptions for launch parameter are required:

Average launch cost targets

The average launch cost targets for SPS are calculated by the difference between the levelized energy costs (LEC) of terrestrial systems and the space based solar power systems without launching costs.

Assumptions for learning curve

Launch fuel costs which base on natural gas as primary energy source will not follow the learning curve for SPS launching but will further increase in future due to resource constraints. Thus, fuel costs are excluded prior to the application of the learning curve on launch costs. Fuel costs are calculated with 64 EUR/$kg_{payload}$ based on a tripling of natural gas prices by 2030. Today's launch costs are assumed with 10,000 EUR/$kg_{payload}$ at current transport mass capacities of 100 tons per year. This represents the lower end of the current range of space transportation costs of some 10 - 20,000 EUR/$kg_{payload}$. The learning curves base on the assumed learning effect of cost reduction for payload transportation of 20% with each doubling of mass capacity. This learning curve was agreed by the various parties involved and is not based on historical experience. An analysis on the viability of the assumed learning parameter values was not in the scope of the study, yet is critical to the overall viability of SPS scenarios discussed therein.

WP1 and WP2 comparison

Figure 0-1 shows the resulting electricity generation costs for terrestrial base load scenarios with solar thermal power plants (SOT) with pumped hydro storage (PH) and hydrogen storage (H_2) respectively. As depicted in the figure the levelized energy costs (LEC) drops for scenarios of higher power levels.

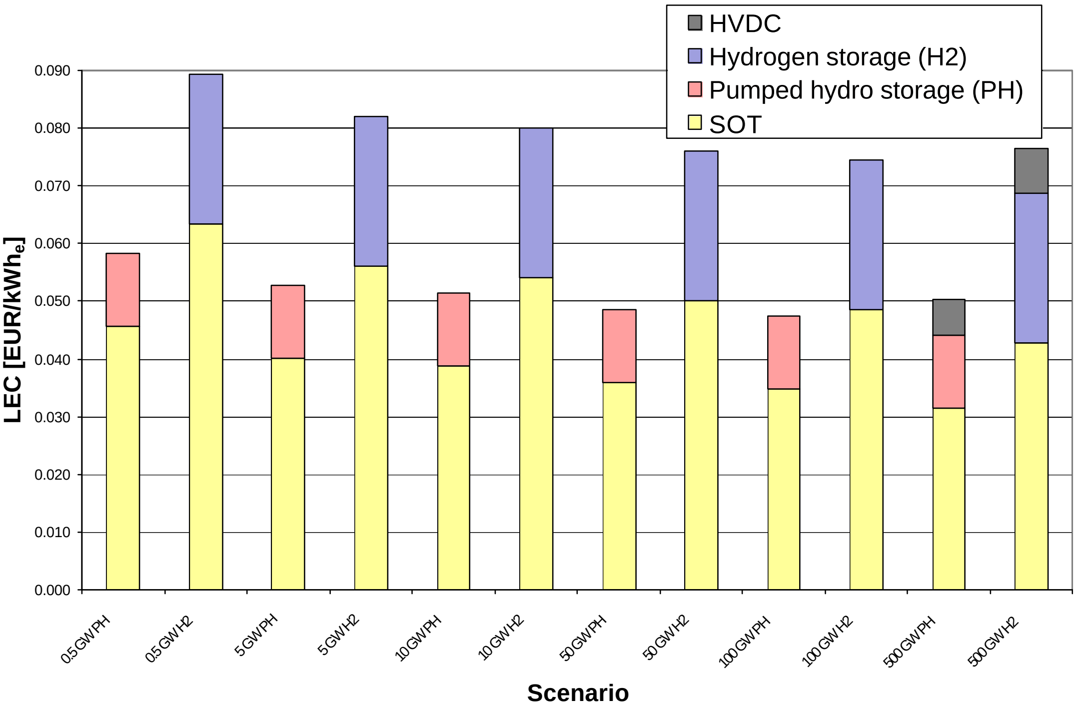

Figure 0-1: Levelized energy costs for terrestrial base load scenarios applying solar thermal power plants (SOT) with pumped hydro storage (PH) and hydrogen storage (H2) respectively

Additionally required HVDC power transmission lines in the 500 GW scenarios increase the total energy costs. The lowest energy supply costs are given for the 100 GW scenarios due to fact that all the required power is generated in Europe and no HVDC is required. Under non-base load scenario conditions, scenario sizes of 10 GW and above, terrestrial PV power production in the European sunbelt is more economic than in North Africa due to higher power transmission costs.

Figure 0-2 shows the results for the space concepts (without launch) for base load scenarios. In contrast to terrestrial scenarios the cost influence of the electricity storage is marginal. Additional electricity storage for SPS systems is only required during eclipse seasons for a maximum period of 70 minutes.

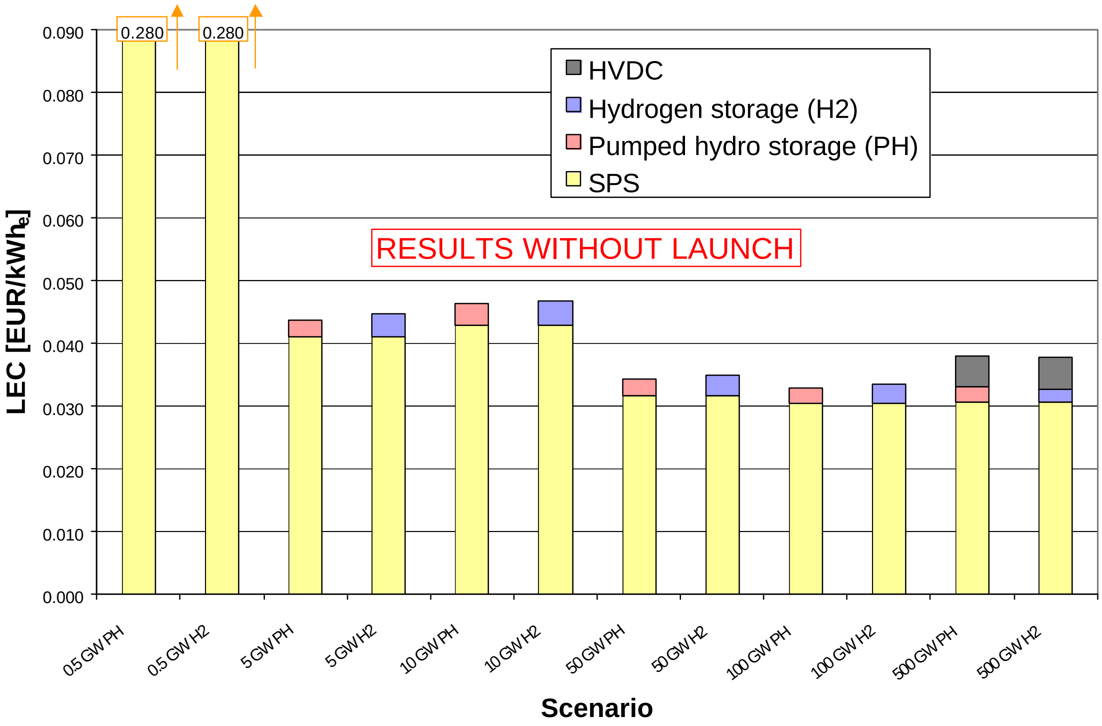

Figure 0-2: Levelized energy costs for space-based base load scenarios applying solar power satellites (SPS) with pumped hydro storage (PH) and hydrogen storage (H2) respectively

The comparison of the LECs of terrestrial and space-based scenarios leads to allowable average launch cost targets for space launching. Except for both of the 0.5 GW space scenarios, which are not competitive even without considering launch costs, the difference of levelized energy costs between terrestrial and space systems results in average launch cost targets for SPS scenarios. Figure 0-3 and Figure 0-4 show these resulting average launch cost targets converted into EUR/kg$_{payload}$ for hydrogen and pumped hydro scenarios respectively.

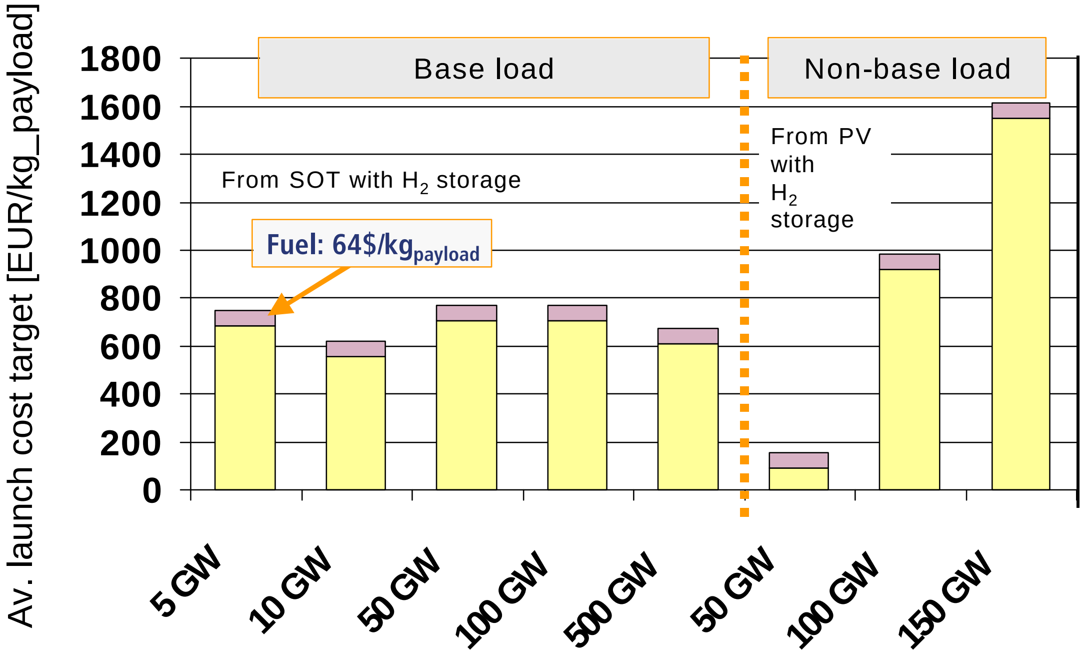

Figure 0-3: Launch parameterization: average launch cost targets for scenarios with hydrogen storage

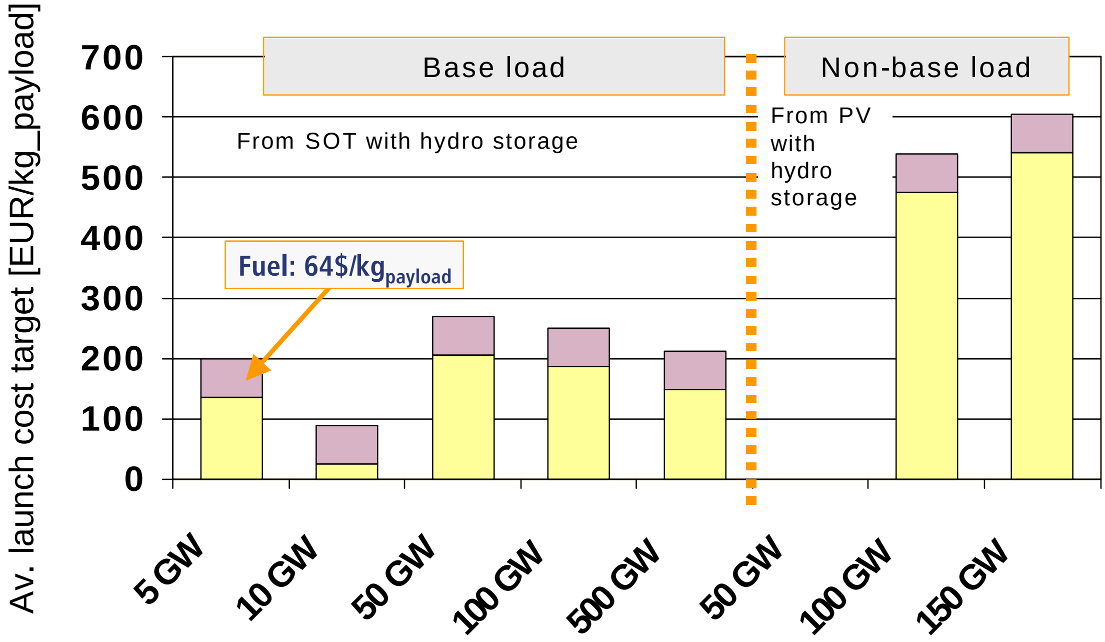

Figure 0-4: Launch parameterization: average launch cost targets for scenarios with pumped hydro storage

The average launch cost targets for SPS scenarios are significant lower with pumped hydro storage options than for hydrogen storage.

The bar graphs in Figure 0-3 and Figure 0-4 illustrate the influence of the fuel costs if fuel costs of 0.9 US$/kg$_{fuel}$ (i.e. 64 US$/kg$_{payload}$) are taken into account. As the fuel costs are assumed not to follow the launch learning curve, the absolute cost share remains constant over scenario size.

Result comparison of base load and non-base load scenarios

Solar power satellite (SPS) systems may be competitive to terrestrial systems for 50, 100 and 500 GW$_e$ base load scenarios if hydrogen storage is selected as terrestrial storage option. Under the scenario definitions given, SPS systems are not competitive to terrestrial base load systems if pumped hydro storage – which is only limited available and not realistic for the 500 GW scenario in Europe – is selected as terrestrial storage. For non-base load scenarios, SPS systems may be competitive to terrestrial photovoltaic systems for 100 and 150 GW$_e$ scenarios if hydrogen storage and for 150 GW$_e$ scenario if pumped hydro storage is selected as terrestrial storage.

	BASE LOAD scenarios	NON-BASE LOAD scenarios
Terrestrial scenario with pumped hydro*)	SPS not competitive to terrestrial scenarios	≥ 100 GW with final launch costs: 323-366 EUR/kg$_{payload}$ **)
Terrestrial scenario with hydrogen storage	≥ 50 GW with final launch costs: 411-480 EUR/kg$_{payload}$ **)	≥ 100 GW with final launch costs: 625-1,060 EUR/kg$_{payload}$ **)

*) pumped hydro is only limited available in Europe
**) final launch costs are based on cost reduction assumptions for expendable launchers

Table 0-1: Space scenarios which are competitive with terrestrial scenarios

Combination of space and terrestrial concepts

Potential synergies due to the combination of space and terrestrial concepts are discussed for both scenarios, base load and non-base load.

For base load as well as non-base load scenarios the substitution of terrestrial electricity storage by SPS systems could result in mutual cost benefits if the excess electricity can be placed in the electricity markets outside Europe or the hydrogen fuel market. If this is not applicable, the SPS system is operated at a lower utilization which would consequently result in higher levelized energy costs.

Another discussed potential synergy is the co-siting of rectenna with large-scale terrestrial solar power plants. The co-siting may reduce rectenna costs due to reduction of total required land area.

For an effective co-siting of rectennae with photovoltaic systems (reference technology for non-base load scenarios), technical obstacles had to be solved beforehand, such as electromagnetic interference and partial shading. However, under the given scenario assumptions co-siting with terrestrial PV systems is not applicable because PV is geographically dispersed throughout the European sunbelt on the basis of decentralized power generation (mostly on roofs and facades). If assuming centralized PV plants in North Africa (see e.g. [Kurokawa 2003]), however, the inability to effectively combine rectennae with photovoltaic power plants would not be very significant economically, since the latters' output per unit area is only a few percent of the rectenna.

The technical feasibility of co-siting rectennae with solar thermal power plants (reference technology for base load scenarios) has to be doubted in principle due to partial shading of direct sunlight.

Major potential synergy effects can be expected due to the common technology basis (i.e. photovoltaic cells). These technological synergies could shorten the time-to-market for terrestrial PV applications from which the terrestrial market would directly benefit.

Complementing the defined base load and non-base load scenarios, further synergies are discussed. Those aspects which go beyond the scope of this study and its scenarios respectively may also offer other potential synergies for terrestrial and/or space scenarios:

‘Renewable electricity mix’ discusses the influence of other energy sources like wind, biomass, geothermal and hydro power which would significantly reduce the storage requirements and consequently the levelized energy costs for terrestrial solar power plants.

The ‘hydrogen option’ would allow hydrogen fuel production from surplus electricity but also the use of hydrogen for combined heat and power (CHP) applications. This may offer the largest synergy effects for both space and terrestrial concepts.

‘Further SPS synergies’ discusses further potential aspects and synergies, including network synergies which could enable satellites to be operated in base load operation mode supplying power to multiple rectennae which could be operated economically even at lower load factors. Thus, further non-base load scenarios may become cost competitive. In addition the use of non-terrestrial materials and the lunar surface could have the potential to greatly reduce the mass of material to be launched from the Earth.

Energy payback

Under the scenario conditions defined throughout this study, the energy payback time of terrestrial and space-based solar power systems are far below their operational lifetimes. For the smallest scenario the energy payback time for SPS is significantly higher than that of terrestrial solar power systems which include electricity storage via hydrogen. For the larger scenarios SPS has a slightly lower energy payback time, see Table 0-2.

Without electricity storage the energy payback period of the solar thermal power plants with central receiver would be approximately one year. If a reference system (replaced electricity from conventional electricity generation) is considered according to DIN, the energy payback time would decrease to about 0.5 years for SPS and to some 0.7 years for the solar thermal power plant with electricity storage via hydrogen in case of the larger scenarios (above 0.5 GW).

		0.5 GW	5 GW	10 GW	50 GW	100 GW	500 GW
TERRESTRIAL	SOT with reference system acording to DIN [years]	0.7	0.7	0.7	0.7	0.7	0.7
	SOT without reference system [years]	1.7	1.7	1.7	1.7	1.7	1.6
SPACE	SPS with reference system acording to DIN [years]	2.0	0.4	0.4	0.4	0.4	0.4
	SPS without reference system [years]	4.4	1.0	1.0	1.0	1.0	1.0

Table 0-2: Energy payback times for terrestrial and space based solar power systems for base load scenarios.

The energy effort for the production of space transportation vehicles dominate the overall energy balance of space based solar power systems. For the energy effort calculation a space transportation vehicle different to that of the selected reference concept (NASA Fresh Look Study) was selected.

The results for SPS are based on a launch vehicle with a payload of 350 t (earth to GEO) and a propellant mass of 4,965 t which lead to a propellant consumption of some 14 t per t of payload. In [NASA 1997] the payload was assumed to be 11.3 t and the propellant mass was assumed to be 804.5 t which lead to a propellant consumption of some 71 t per t of payload. This led to energy payback times for space-based solar power systems even below the energy payback figures of solar thermal power plants (see Figure 0-5).

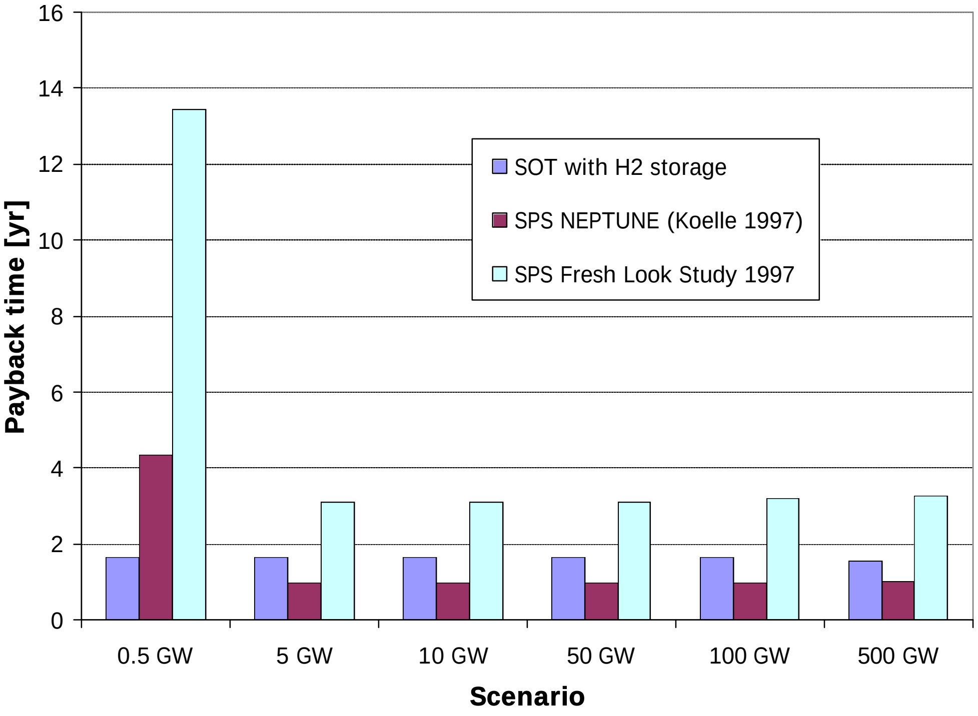

Figure 0-5: Influence of the launch vehicle on the energy payback time (without considering a reference system)

The energy backpack time of SPS concepts strongly depend on the assumed launch vehicle. However, the payback time for all variants of electricity generation from solar power is far below the lifetime of the plants (30 years).

Reliability and risk

It is in the nature of this study that evidence on this issue is difficult for at least two inherent reasons: the widely different technological state-of-the-art, and due to the systems' structurally different constitutions (PV/SOT which small in size but large in terms of number of power units vs. SPS which is diametric to terrestrial power systems, large in size and small in terms of number of power units). Central issues which are in the focus of discussion are: Can the technical and costs targets be achieved (especially space transportation), system failure tolerance as well as vulnerability towards sabotage/terror attacks, environmental and health risks, interference due to microwave power transmission and geo-political implications.

Microwave technology requires further detailed risk discussion and assessments including safety aspects and threats for human health and environment, public acceptance as well as potentially technological risks, mainly due to electromagnetic interference.

Any energy conversion technology requires a certain amount of up-front investment for research, development and implementation until the first kWh is supplied. The higher the up-front investment, the higher are its economic risks. Due to the current technological state-of-the-art as well as due to the technology inherent large size of a single power unit, SPS specific up-front investment is significantly. Economic risks for solar power satellite scenarios should thus be investigated and discussed in more detail.

Even when assuming that the development and installation of space-based solar power systems proceeds as planned, there is still the time risk. SPS may – aside others – well be a solution to ease the burden of human energy consumption on the environment. Yet, potential benefits from SPS require a long lead-time at inherently higher risks due to its technical state-of-the-art. There are two resulting risk pathways: the risk of omission and the risk of misdirected investment. If governments decided to proceed on a business-as-usual basis until 2030 when SPS is finally up and running – there would be the risk of facilitating climate change, air pollution etc. If government decided to facilitate investments in terrestrial renewable energies and energy savings in order to environmentally benefit as fast as possible – then the risk is that there is no longer a market demand for SPS. A balanced policy of investing in a portfolio of energy technologies is optimal.

Little scientific knowledge exists about the significance of air pollution ('global dimming') on microwave power transmission and the output of terrestrial solar power plants for the projected timeframe. There are three major risks which differentially face the terrestrial solar option. The use of up to 100,000 km^2 for power generation via SOT plants (see Table 10-4) has no precedent in Europe. In view of resistance to wind power generation even at current lower levels, the risk of public-non-acceptance of large land use for SOT plants needs to be considered. Second there is a geo-political risk facing the use of very large areas of land in the south of Europe (and even North Africa) to supply power to the North. Political feasibility is unknown. Third, a well recognized risk of climate change caused by global warming is the possibility of increased cloud cover. This could substantially reduce the power output of all terrestrial solar power systems, but would have no effect on space-based solar power supply using microwave power transmission.

When discussing risks, a strong emphasize is to be put on the political, legal and military consequences which may even arise if space activities are destined as civil space development only. Most of these risks apply to any broad-scale utilization of space. The entrance barrier to military utilization of space is eventually lowered no matter how noble the motivation might have been initially. Outer space is identified as strategic key area for military operations. Deficits in international space legislation and arms control in outer space exist. Space-based solar power systems require a multi-national alliance for research, development and operation. The alliance has to be embedded in a strong legal framework which is transparent and also internationally accepted by third-party states.

Implications from scenario specifications

Non-base load scenario design implies extremely pessimistic cost figures for space-based solar power. Reasons for this are the very low system utilization especially at smaller scenario sizes and the geographic limitation on Europe solely. This also applies to terrestrial solar power plants, yet to a lower magnitude.

The development of new low cost reusable space vehicles would offer higher cost reduction potentials for space transportation as assumed for the comparison with terrestrial systems. Thus, different learning curves for space transportation would be given and result to lower allowable final launch cost targets. Furthermore network synergies of solar power satellites would make SPS systems far more economic for non-base load operation and competitive to terrestrial scenarios.

Overall scenario design implies rather conservative cost figures for terrestrial solar power. This is determined by mainly three reasons: Focus is put on one terrestrial power solely. Conventional power supply schedules (base load/non-base load) which are likely no more applicable at a rising penetration of renewable energies. And the type of terrestrial energy assessed (wind, biomass or geothermal, would already start at significantly lower generation costs). Consequently, especially for base-load scenarios the resulting cost targets for space transportation are likely more demanding. A more realistic scenario of autonomous terrestrial sustainable energy supply for Europe would shed light on the sensitivity of results – i.e. one not dependent solely on solar power, but making the optimal use of all energy sources available. Furthermore, the consideration of renewable energy demand for transportation purposes and the supply of renewable energy to non-European countries could provide a better basis for considering the possible value and validity of developing space-based solar power systems.