EARTH & SPACE-BASED POWER GENERATION SYSTEMS – A COMPARISON STUDY

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ABSTRACT/RESUME

The objective of the study [1] 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.

The 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.

The comparative cost, energy, risk and reliability discussions and evaluations are based on highly asymmetrical input data due to different magnitudes of practical experiences.

However, under the study assumptions given, space-based solar power systems may potentially provide a firm power supply and could be economically competitive to terrestrial solar power systems if space transportation costs in the lower hundreds EUR/kg payload are achieved. The energy payback time could be in the range of other solar power technologies far below their operational lifetimes. Risks attributed with SPS are mainly in the field of health and public acceptance of microwave power transmission, the general R&D risk and geopolitical implications.

1. INTRODUCTION

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 more than two billion people have no access to electricity. This people do not directly participate in the consumption of energy. In 2030 some eight billion people 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 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 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 peak. 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. Renewable energies have the potential to meet these challenges. Thereby, great progresses have been made in the field of solar energy technologies since the 1960ies. Compared to terrestrial solar power systems, space based solar power systems achieve higher power conversion efficiencies. Outside the earth's atmosphere solar irradiation is significantly higher compared to the earth's surface. In space based solar energy systems the energy may be transmitted to Earth by means of microwave beam or a laser.

2. STUDY APPROACH AND METHODOLOGY

The goal of the study [1] is to comparatively assess terrestrial and space based solar power systems regarding economic viability, energy investment, risks and reliability. The overall scope of the project was split into four work packages.

	Terrestrial based solar power systems	Space based solar power systems
Work package I	Base load	Base load
Work package II	Non-base load	Non-base load
Work package III	Combined scenarios: Synergies	
Work package IV	Energy payback	Energy payback

Fig. 1. Overview of work packages and study objectives.

In work package I and II, terrestrial and space based solar power system architectures are designed and assessed on the basis 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. A discussion of risk and reliability issues is led separately.

2.1 Definitions for work packages I and II

For the comparison of space based solar power systems with terrestrial solar power systems, two basic scenario cases are defined: base load (WP1) and non-base load (WP2) operation only. For base load scenarios 0.5 GW_e, 5 GW_e, 10 GW_e, 50 GW_e, 100 GW_e and 500 GW_e power levels are evaluated. For non-base load scenarios the power levels 0.5 GW_e, 5 GW_e, 10 GW_e, 50 GW_e, 100 GW_e and 150 GW are considered. The definitions for WP1 and WP2 also include the limitation to compare solar power satellites (SPS) systems only 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 needs and costs for terrestrial scenarios due to the fact that terrestrial storage is a major cost driver. Thus this comparison marks an extreme.

The launching of solar power satellites is defined as a key parameter and excluded from scenario comparisons. All cost statements for space systems are primarily evaluated without launch and added as a parameter. The consortium decided to display the total allowable launch cost targets of space systems to be competitive with terrestrial scenarios. This cost targets are translated into learning curves resulting from this competition.

2.2 Definitions for work package III

The aim of WP3 is to identify synergies between the operation of terrestrial solar power plants and the delivery of solar power from space apart from the restrictions of WP1 and WP2 where a defined demand profile had to be met while using only one single energy source. After looking at the results from WP1&2 it became clear, that the original WP3 idea – to find a operation mode between terrestrial and space solar power side by side to create an optimized benefit – had to be modified as no mutual benefits could be identified by combining the two systems straightforward.

Nevertheless, from the perspective of the respective system there are synergies that could optimize the selected system at least in delivering a new and additional benefit to that system. It was considered as a solution to subdivide WP3 into “synergies from terrestrial perspective” and “synergies from space perspective”. The resulting synergies now have to be seen from the perspective of the respectively selected system.

The need for a more advanced interpretation of the term “synergies” was identified in both systems, space and terrestrial. Therefore, the original scope of the study was supplemented by a new chapter “Alternative Scenarios” which discusses synergies between space and terrestrial plants in a broader sense and comprises additional aspects.

2.3 Definition for work package IV

In work package IV the energy payback times of the selected concepts are determined and compared. Therefore, a life cycle analysis was conducted comprising the material and energy effort required for construction, installation and maintenance of the systems.

In contrast to the methodology of launch parameterization applied for the WP1 and WP2 comparison specific launch assumptions had to be made for energy related calculations in WP4. Within the comparison different launch vehicles have been considered to indicate a bandwidth for the launch energy needs.

2.4 General definitions and assumptions

Various **photovoltaic** (PV) technologies are already available on the market or within reach of market penetration within the next decade. All improvements or new technologies pave the way to reduce the costs per kWh_e. Whether by increase of efficiency or by reducing production costs. For terrestrial scenarios conventional and available technologies have been considered. A learning curve and a resulting cost degression of 20% for each doubling in production capacity has been generally agreed within this study and is proven historically.

For space installations only thin film technologies with very light substrates (metal or polymer) have been considered. This technologies are still under development today. Prototype cells in laboratory scale already have shown success in operation. The next step must be the transfer of production technology to larger industrial scales. 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.

Four different technologies of **solar thermal** (SOT) power plants are discussed and described for terrestrial concepts: parabolic trough, central receiver, parabolic dish and solar power tower (solar chimney power plants). After a detailed evaluation of the favored parabolic trough and central receiver technology, solar power plants based on the central receiver concept with integrated 13 hours thermal storage capacity was selected for terrestrial base load scenarios. Major cost reduction potentials of around 50% for evaluated base load scenarios are identified for the heliostat field of the central receiver plants.

For the space scenarios two different **SPS concepts** are selected from the NASA Fresh Look Study [2]. For the smallest scenarios of 0.5 GW_e eight ‘Sun Tower’ in medium altitude earth orbit (MEO) designed to provide 250 MW_e are selected. For all other power levels several modular ‘Solar Disk’ systems in geo-stationary earth orbit (GEO) scaled for a power supply of 1 GW_e, 5 GW_e and 10 GW_e are chosen.

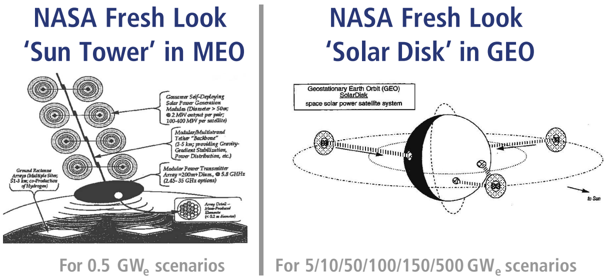

Fig. 2. Selected SPS reference architectures.

For space based systems a **power transmission** from space to earth via microwaves was selected analogue to the reference SPS concepts described in the NASA Fresh Look Study. Laser technology or other concepts of power transmission are not considered and evaluated. Both SPS concepts transmit power via microwave beam at a frequency of 5.8 GHz to rectennae analogue to the NASA reference systems. The critical power density limit at the fence of the rectenna generally is determined by local regulations. This study includes the NASA assumptions of 1 W/m^2 .

For base load and non-base load scenarios the following satellite : rectennae ratios are selected: 4:1 for ‘Sun Tower in MEO’ concept (each 250 MW_e), 1:1 and 2:1 for ‘Solar Disk in GEO’ concept (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, is additionally discussed in this study.

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.

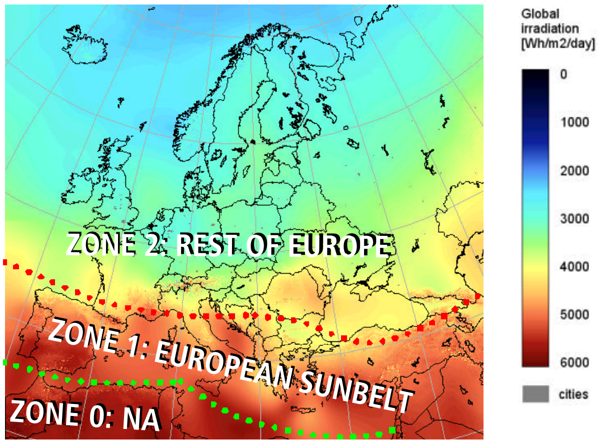

Fig. 3. Geographical distribution of solar irradiation and definition of 'sun zones' (PV-GIS modified by LBST).

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 irradiation values in the course of a whole year. Sun zone 1 comprises the countries in the European sunbelt – these are Portugal, Spain, Italy, Greek and Turkey. Especially Turkey may provide large potentials on high solar irradiation. Sun zone 2 subsumes the rest of Europe without the countries in the European sunbelt.

Within the evaluation of locations for solar thermal (SOT) power plants it was emphasized to use zone 1 to be independent from energy imports to the highest possible level. Nevertheless, for the 500 GW_e scenario it was selected to include northern African territories. The predominant European installation also showed advantages in lower energy transportation needs.

We assume, that the European **high voltage electricity grid** will be continuously enforced due to the requirements of a step by step deregulated single European energy market. Furthermore, the growing quantity of renewable energy from volatile sources, such as wind and biomass, will also have to be fed into the grid. This will also require a powerful European backbone electricity grid until 2030.

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 highly risky for the stability of the electricity grid and the security of energy supply.

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

For scenario calculation, the virtual single European **power demand** had to be synthesized ('EUROPE-2030'). Primary data is provided by transmission system operators (TSO). For the evaluation of the power transmission throughout Europe via HVDC the local power consumption is considered and subtracted from the locally produced power to reduce the amount of electricity which is finally transmitted via HVDC.

For the continuous base load power supply of 8,760 full load hours per year as well as for concepts optimization for non-base load scenarios additional energy **storage** capacities are required and selected. Various electricity storage technologies are discussed for their application for the scenarios including 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 the scenarios: hydrogen has been selected as energy storage because it can be stored over a very long time without any energy loss (in contrast to batteries which have a self-discharge) and the energy density is higher than that of other electricity storage technologies. Flexibility is 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). Pumping storage has been selected because pumped hydro storage plants have a high loading/unloading cycle efficiency and are already in operation for many years. Yet, the use of pumped hydro is subjected to geographical conditions.

It was agreed only to take the **use of land** into account which is required for power transmission. The cost shall be taken into account with 10 EUR/m².

3. SCENARIO ASSESSMENT

For terrestrial WP1 base load scenarios modular solar thermal (SOT) power plants with 220 MW_e gross output are selected mainly because of their higher solar capacity factors compared to photovoltaic (PV) systems. Thereby, central receiver with integrated thermal storage achieve the highest amount of full load hours of around 6,400 hours per year.

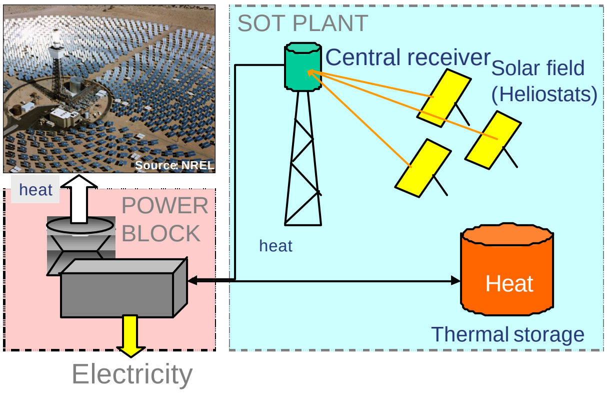

Fig. 4. Selected terrestrial solar power concept for base load: central receiver with thermal heat storage.

For WP2 'non-base load' scenarios low annual equivalent full load hours are given for the systems. The maximum considered scenario power level for 'non-base load' operation is 150 GW_e. For terrestrial WP2 scenarios photovoltaic (PV) systems are mainly selected due to their high modularity. For WP2 space based systems the same concepts are chosen as for WP1. Thereby, the load factors for non-base load systems are adapted to the WP2 capacity factors for each power level ranging from 5 h/yr for the 0.5 GW_e scenario to 1,730 h/yr for the 150 GW_e scenario.

For additionally required electricity storage capacities for the terrestrial as well as space based scenarios two different storage concepts are selected and evaluated. 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. The other evaluated storage option 'pumped hydro' considers the use of pumped hydro power plants. All scenarios include the investment costs for the building of new pumped hydro plants.

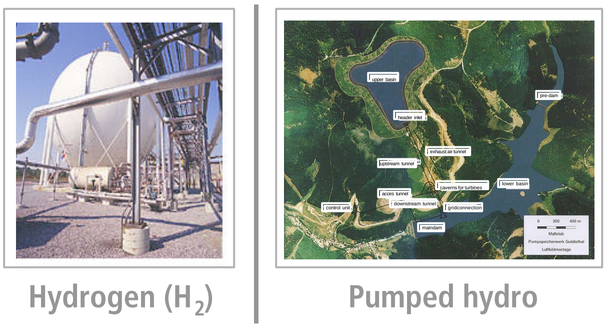

Fig. 5. Selected storage options for additionally required power storage: hydrogen and pumped hydro storage.

Terrestrial solar power plants as well as SPS-rectennae are favorably sited throughout the European sunbelt comprising Portugal, Spain, Italy, Greece and Turkey. Compared to installations in zone 0 'North Africa' power transmission via HVDC can be reduced or even avoided which reduce the costs of electricity supply and losses due to power transmission. Furthermore, political risks are reduced as well as higher power supply security are given if power installations are sited throughout Europe. Compared to plant installations in zone 2 'rest of Europe' higher solar irradiation in zone 1 leads to higher efficiencies for terrestrial power plants. Except from the 500 GW_e base load scenarios all required SOT plants could be installed in zone 1 only. Additionally required SOT capacities ranging between 100 to 220 GW_e are sited in zone 0 'North Africa' because of the low solar irradiation for SOT plants of zone 2 locations. For all non-base load scenarios PV plants are only installed in Europe throughout zone 1 with highest irradiation in Europe. 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. Rectennae sited in zone 1 are using same land area potentials analogue to 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.

4. 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 etc. The study solely focuses on the calculation of space transportation cost targets which would have to be realized in order to achieve economic competitiveness with terrestrial solar power generation systems.

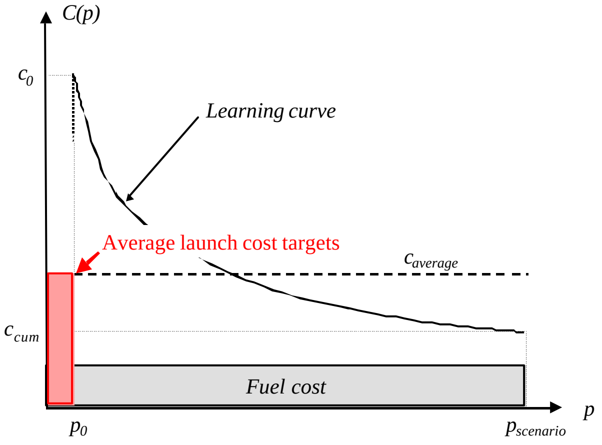

Fig. 6. Learning curves for SPS launching.

For the calculation of the learning curve average launch cost targets ($c_{average}$) as well as assumptions for launch parameter (c_o, p_o, learning effects) are required as following:

4.1 Average launch cost targets

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

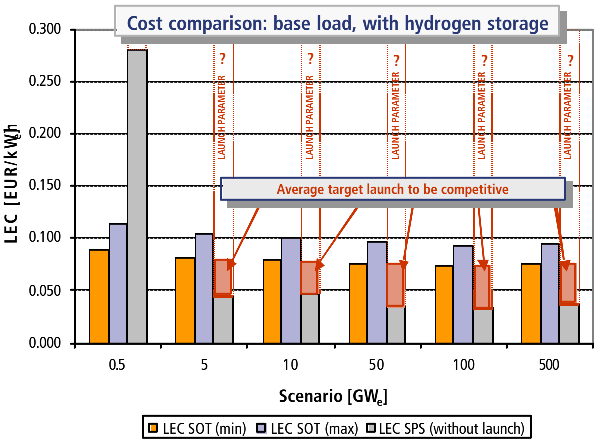

Fig. 7. Cost comparison of base load scenarios with hydrogen storage for the calculation of average launch cost targets.

Allowable average launch cost targets for SPS systems are higher for scenarios with hydrogen storage (Fig. 6) and lower for scenarios with pumped hydro storage (Fig. 8) where those are feasible.

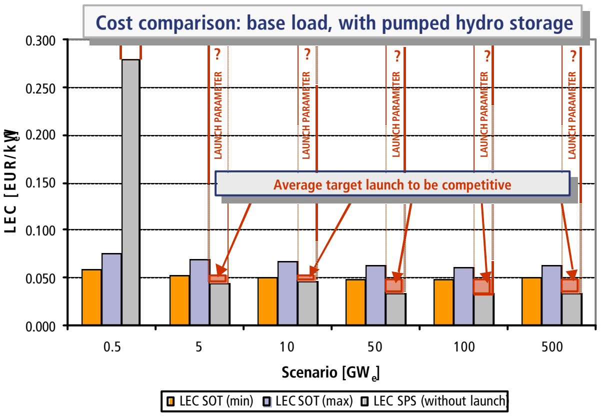

Fig. 8. Cost comparison of base load scenarios with pumped hydro storage for the calculation of the average launch cost targets.

Fig. 9 and Fig. 10 show the resulting average launch cost targets for SPS launching in order to be competitive with terrestrial solar power systems.

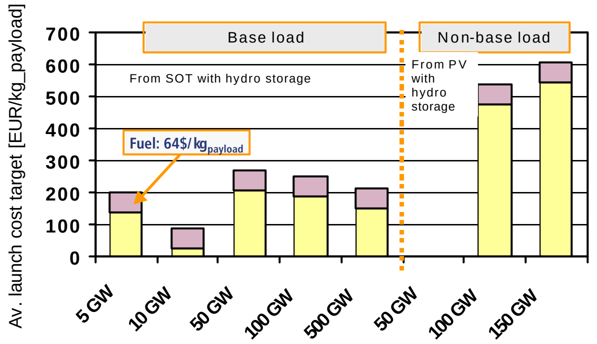

Fig. 9. Average launch cost targets for scenarios with pumped hydro storage.

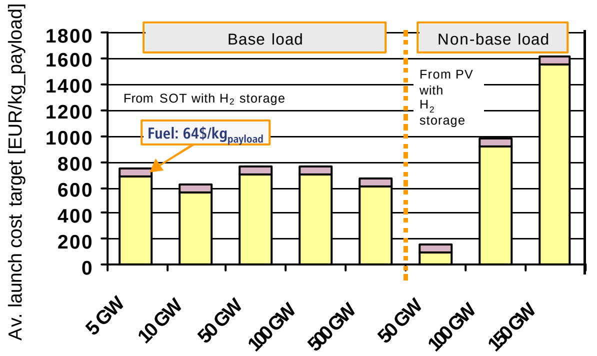

Fig. 10. Average launch cost targets for scenarios with hydrogen storage.

The fuel cost share 64 EUR/$kg_{payload}$ are subtracted from the resulting average launch cost targets which are required for SPS launch learning curves. Fuel costs will not be reduced due to the same learning factor as space transport infrastructure.

4.2 Learning curve assumptions

Launch fuel costs which base on natural gas as primary energy source will not follow the learning curve for SPS launching but will likely increase until 2030. Thus, targeted launch learning curves for launch costs do not include fuel costs. Fuel costs are calculated with 64 EUR/$_{\text{kgpayload}}$ based on an assumed tripling of natural gas prices in the following decades. Today's launch costs are assumed with 10,000 EUR/kg$_{\text{payload}}$ at current transport mass capacities of 100 tons per year. This represents the lower end of the current range of space transportation costs of 10 - 20,000 EUR/kg$_{\text{payload}}$. 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. However, a change to new launch technology would shift to a different learning curve.

5. RESULT COMPARISON OF BASE LOAD AND NON-BASE LOAD SCENARIOS

Under the study's scope and assumptions, solar power satellite systems may be competitive to terrestrial systems for 50, 100 and 500 GW$_e$ base load scenarios with selected hydrogen storage option. SPS systems are not competitive to terrestrial base load systems with selected pumped hydro storage option, where those are feasible. For non-base load scenarios SPS systems may be competitive to terrestrial photovoltaic systems for 100 and 150 GW$_e$ scenarios with selected hydrogen storage and for 150 GW$_e$ scenario with pumped hydro storage option, where those are feasible.

Tab. 1. SPS scenarios competitive with terrestrial scenarios.

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

*) availability of pumped hydro storage is subject of geographical limits in Europe

**) final launch costs are based on cost reduction assumptions for expendable launchers

6. 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 could be placed in the electricity markets outside Europe or the hydrogen fuel market (both beyond the scope of the study). 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 required land area. However, the technical feasibility of co-siting rectennae with solar thermal power plants has to be doubted in principle due to partial shading of direct sunlight. And for an effective co-siting of rectennae with photovoltaic systems, 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. Ref. [3]), however, the inability to effectively combine rectennae with photovoltaic power plants would not be very significant economically, since the latter's output per unit area is only a few percent of the rectenna.

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 PV 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 dramatically reduce the levelized energy costs for terrestrial power plants.

The '**hydrogen option**' would allow to consider the 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 use of non-terrestrial materials and the lunar surface, which could have the potential to greatly reduce the mass of material to be launched from the Earth. Network synergies would 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.

7. 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. Space-based solar power systems' energy payback times are 1.0 year (0.4-0.5 years according to DIN) except for the 0.5 GW scenario where it is 4.4 years (2.0 years according to DIN). Solar thermal power plants' energy payback times are between 1.6 - 1.7 years (0.7 years according to DIN) including hydrogen storage. If considering SOT without storage, the resulting energy payback times are 1.0 - 1.1 years (0.4 – 0.5 years according to DIN).

The energy effort for the production of space transportation vehicle dominates the overall energy balance of **space based solar power systems**. For the energy effort calculation a space transport vehicle different to that of the selected reference concept (NASA Fresh Look Study) was selected. For the selected launch vehicle NEPTUNE a payload capacity of 350 tons to GEO and a fuel consumption of 14 tons per ton of payload was assumed. The launch vehicle assumed in the NASA Fresh Look Study has been assumed to be 11.3 tons of payload capacity to GEO and a fuel consumption of 71 tons of fuel per ton of payload. The result from energy payback calculation for space-based solar power systems was thus significantly lower than the energy payback figures of solar thermal power plants, see Fig. 11.

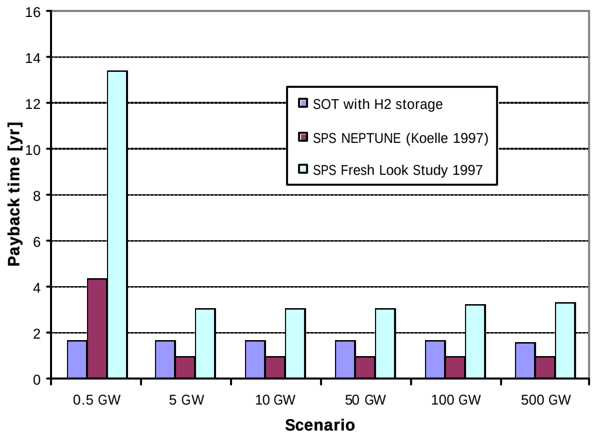

Fig. 11. Energy payback times for different launch vehicles and terrestrial solar thermal power plants.

The energy effort for **terrestrial solar power systems** is dominated by the storage systems (hydrogen as well as pumped hydro storage). The storage requirements are implied by an 'artificial' scenario design which is far off reality. Storage requirements of this size are only likely in off-grid or so-called 'island' applications.

The **net energy balance** during the installation period was calculated for terrestrial and space systems. To achieve a positive net energy balance at any time the maximum growth rate for SPS was calculated with 73% considering a construction time of two years for a 5 GW_e SPS system; 60% for a 108 MW_e solar thermal power plants and 40% for a 750 MW_e photovoltaic system, each with a construction time of one year. The conclusion is that the scenario relevant total capacities are easily installed while still keeping a positive net energy balance for each year except during the first 3 - 4 years. But at these initial years the annual energy requirement is negligible compared to the annual output after 25 years.

8. RELIABILITY AND RISK

It is in the nature of this study that evidence on this issue is difficult for at least two inherent reasons: first, due to the widely different technological state-of-the-art, and secondly, 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, geo-political and military implications.

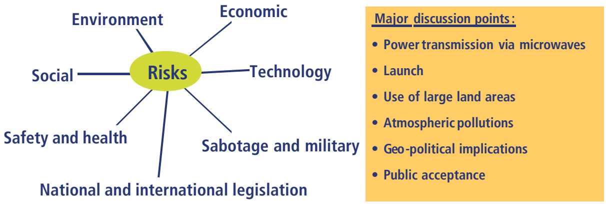

Fig. 12. Risk categories (left) and issues (right)

Major risks discussion should focus on microwave technology and the space systems. On the one hand 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 given due to electromagnetic interference. On the other hand, especially economic risks for solar power satellite scenarios should be investigated and discussed in more detail. Due to the current technological state-of-the-art as well as due to the technology inherent large size of a single power unit possible, high up-front investment is required for commercialization. Any technology and cost target which is not met would eventually result in significant financial losses.

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. Either society decides to proceed on a business-as-usual basis until 2030 when SPS is finally up and running – then there is the risk of facilitating climate change, air pollution etc.; or society decides 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.

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 km² for power generation via SOT plants 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 need 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 developments only. 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. 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. Deficits in international space legislation and arms control in outer space exist. International space legislation activities to overcome this regulatory deficit for the sake of a civil utilization of space have come to a halt due to the interests/fear of a military utilization of space by major states.

9. IMPLICATIONS FROM SCENARIO SPECIFICATIONS

Scenario design implies rather pessimistic cost figures for terrestrial solar power. This is given by mainly three reasons:

1) Focus is put on one terrestrial power solely

2) Conventional power supply schedules (base load / non-base load) which are likely no more applicable at a rising penetration of renewable energies

3) The type of terrestrial energy assessed (solar). Others, such as wind, biomass or geothermal, would already start at significantly lower generation costs

Consequently, the resulting cost target for space transportation is 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. This would be less constrained than a purely solar scenario, and could provide a better basis for considering the possible value of developing space-based solar power systems. Furthermore, hydrogen generation may provide novel opportunities in combination with the electricity market. By now, the hydrogen option is largely untapped by SPS research efforts.

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