EARTH & SPACE-BASED POWER GENERATION SYSTEMS
A COMPARISON STUDY

A Study for ESA Advanced Concepts Team

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Final Report

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ACRONYMS AND ABBREVIATIONS

a	Anno, Year
AC	Alternating Current
AIT&E	Assembly, Integration, Testing and Evaluation
AM 1.5	Air Mass 1.5 (full atmosphere)
AOCS	Attitude & Orbit Control System
AWG	American Wire Gauge
bEUR	billion Euros
BOP	Balance Of Plant (see BOS)
BOS	Balance Of System (see BOP)
C&DH	Command & Data Handling
CCGT	Combined Cycle Gas Turbine power plant
CDEP	Concept Development and Evaluation Program
CFRP	Carbon-Fibre Reinforced Plastics
CGH_2	Compressed Gas Hydrogen
CHP	Combined Heat and Power
CIGS	$CuIn_{(1-x)}Ga_{(x)}Se_2$ (solar cell technology)
CNES	(France) Centre National d'Études Spatiales
COPUOS	(UN) Committee on the Peaceful Utilization of Outer Space
CR	Central Receiver Solar Power Plant
CRES	Chemically-Rigidized Expandable Structures
CVD	Chemical Vapor Deposition
DC	Direct Current
DIN	Deutsches Institut für Normung (German Institute for Standardization)
DNA	De(s)oxyribonucleic Acid
DoE	(US) Department of Energy
e.g.	exempli gratia (Latin: "for example")
EC	European Commission
EEX	European Energy Exchange
EFG	Edge-defined Film Growth
EGS	Electronic Grade Silicon

EJ	Exa-Joule = 10^{18} Joule
EMC	Electromagnetic Compatibility
EMF	Electromagnetic Fields
EOL	End Of Life
ESA	European Space Agency
ESTEC	(ESA) European Space science & TEchnology Center
ETLO	Earth to Low Orbit
EU	European Union
EVA	Ethylene Vinyl Acetate
FAO	(UN) Food & Agriculture Organization
FC	Fuel Cell
FIRST	(ESA) Far InfraRed Space Telescope
FMEA	Failure Mode & Effects Analysis
GEO	Geosynchronous Earth Orbit
GHG	Greenhouse Gas(es)
GNP	Gross National Product
GW_e	Gigawatts Electrical
GWh	Gigawatt-hour
H_2	Hydrogen
H_2O	Water
HLLV	Heavy Lift Launch Vehicle
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
i.e.	id est (Latin: "that is")
ICE	Internal Combustion Engine
IMT	(University of Neuchâtel) Institute of Microtechnology
ISIS	(NASA) Inflatable Sunshield In Space
JSC	(NASA) Lyndon B Johnson Space Center
kW_e	Kilowatts Electrical
kWh	Kilowatt-hour
LBST	Ludwig-Bölkow-Systemtechnik
LEC	Levelized Electricity Costs
LEO	Low Earth Orbit
Lf	Learning factor

LH_2	Liquefied Hydrogen
LO_2	Liquefied Oxygen
LOX	Liquefied Oxygen
LPS	Lunar Power System
LWR	Light Water Reactor
MCBC	Marco C Bernasconi Consultants
MEO	Medium-altitude Earth Orbit
METI	(Japan) Ministry of Economy, Trade and Industry
MH	Metal Hydrides
MLI	Multi-Layer Insulation
MSFC	(NASA) Marshall Space Flight Center
Mto_e	Million tons of oil equivalent
MW	Megawatt, Microwave
MW_e	Megawatts Electrical
MWh	Megawatt-hour
na	not available, not applicable
NASA	(US) National Aeronautics & Space Administration
NB	Nota Bene (Latin: "note well", "take notice")
NIMBY	Not In My Back Yard
NO_x	Nitrogen Oxide
NPV	Net Present Value
NRC	(US) National Research Council
NREL	National Renewable Energy Laboratory
NWD	Nuclear Waste Disposal
O&M	Operation and Maintenance
OECD	Organisation for Economic Co-operation and Development
OTA	(US) Office of Technology Assessment
OTC	Over The Counter
OTEC	Ocean Thermal Energy Conversion
p.	page
PE	Primary Energy
PEM(FC)	Proton Exchange Membrane (Fuel Cell)
PH	Pumped Hydro Storage
P-h	Pumped Hydro Storage

PR	Performance Ratio
PS	Pumped Hydro Storage
PSA	Pressure Sensitive Adhesive
PSU	Pressurization System Unit
PV	Photovoltaics
rf	Radio Frequency
ROC	Rigidization On Command
S&L	Sargent & Lundy, see [S&L 2003]
SEPS	Solar Electric Propulsion System
SERT	Space solar power Exploratory Research and Technology
SFC	Space Future Consulting
SGS	Solar Grade Silicon
SOT	Solar Thermal
SOW	Statement of Work
SPS	Space (or Solar) Power Satellites, Space (or Satellite) Power Station
SSME	Space Shuttle Main Engine
SSPS	Satellite Solar Power Station
STC	Standard Test Conditions
TCO	Transparent Conductive Oxide
TFPV	Thin Film Photovoltaics
TFS	Thin Film Silicon
TNC	Thomas Nordmann Consulting
TWh	Terawatt-hour
UHI	Urban Heat Island (Effect)
UPS	Uninterruptible
UV	Ultra Violet
VAB	(NASA) Vehicle Assembly Building
vs.	versus
WP	Work Package
WPT	Wireless Power Transmission
yr	Year

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.

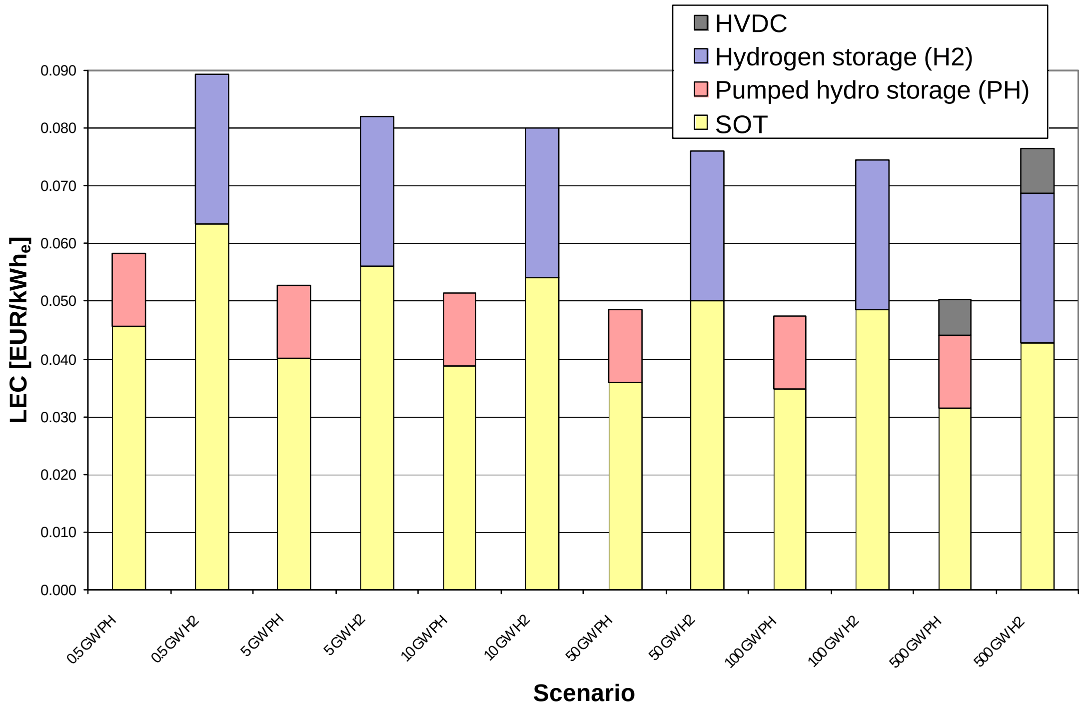


Figure 0-1: Levelized energy costs for terrestrial base load scenarios applying solar thermal power plants (SOT) with pumped hydro storage (PH) and hydrogen storage (H2) respectively

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.

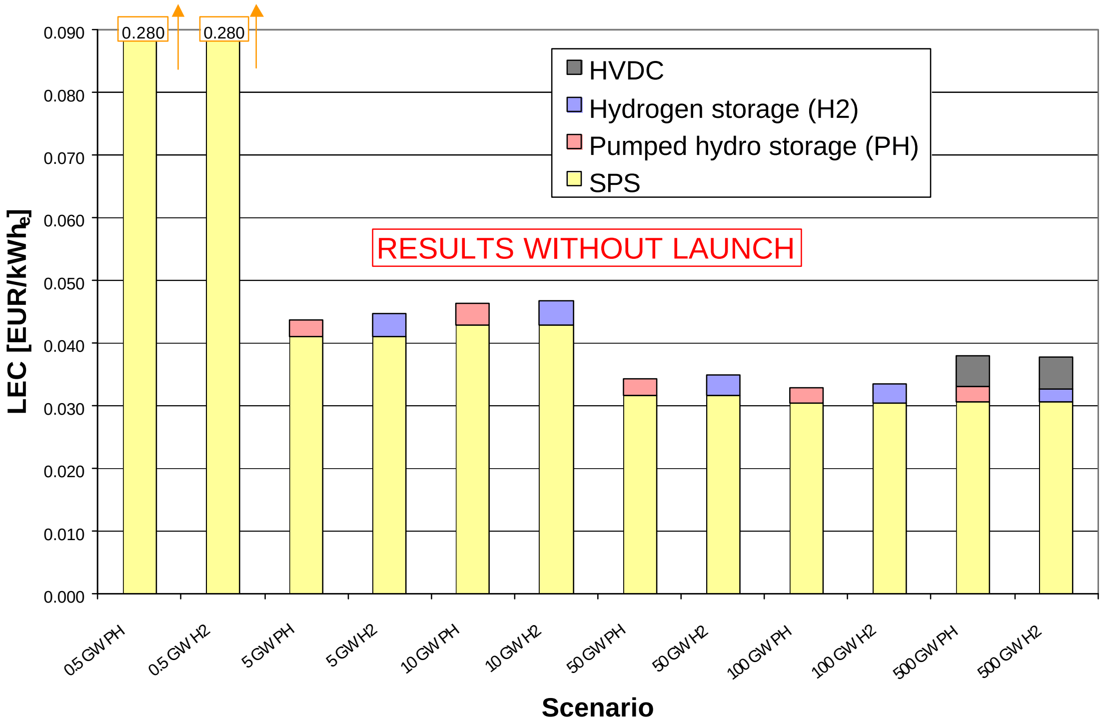


Figure 0-2: Levelized energy costs for space-based base load scenarios applying solar power satellites (SPS) with pumped hydro storage (PH) and hydrogen storage (H2) respectively

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.

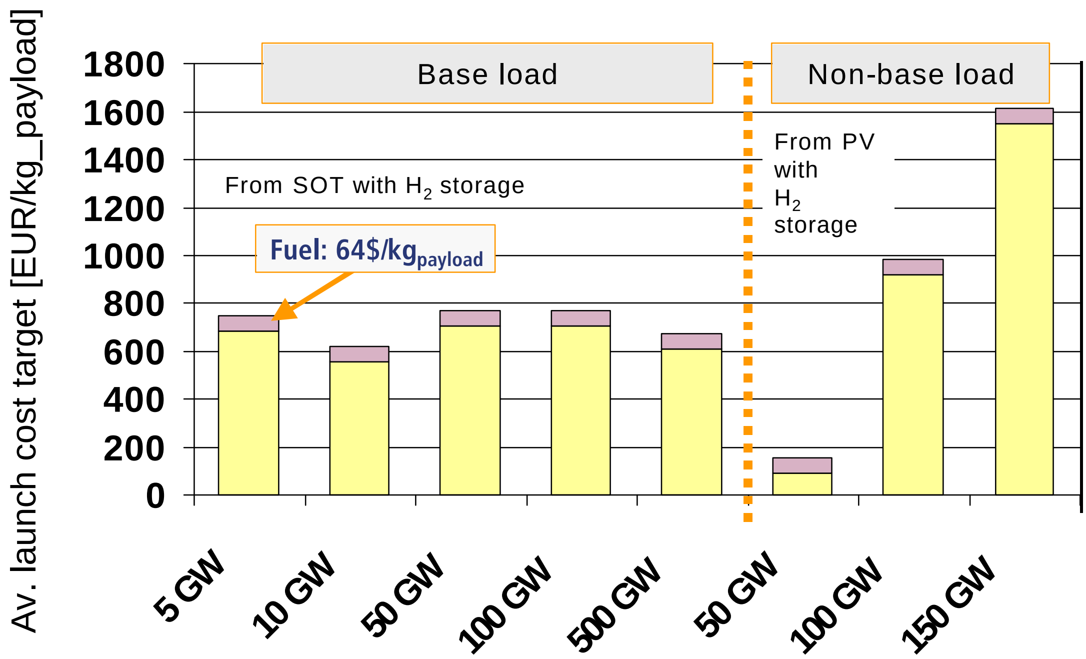


Figure 0-3: Launch parameterization: <u>average</u> launch cost targets for scenarios with hydrogen storage

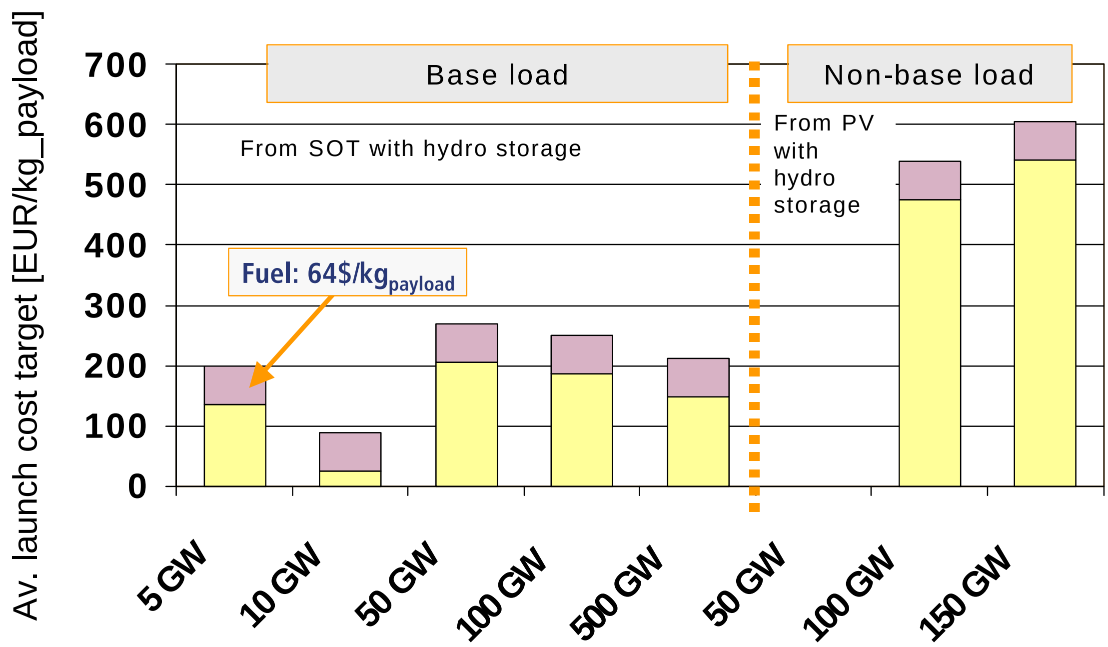


Figure 0-4: Launch parameterization: <u>average</u> launch cost targets for scenarios with pumped hydro storage

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).

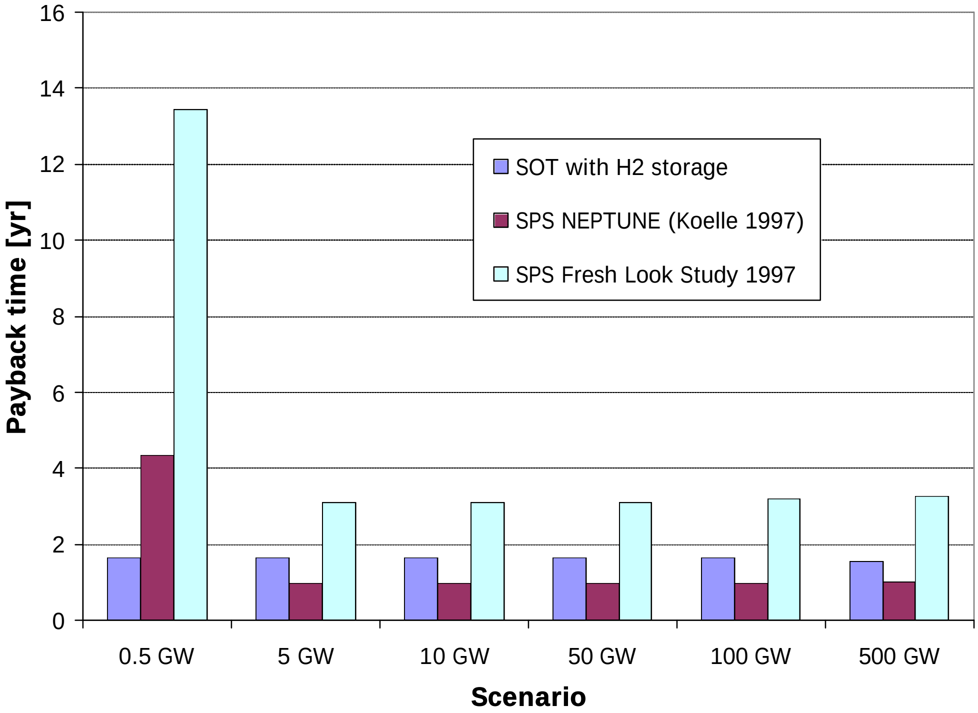


Figure 0-5: Influence of the launch vehicle on the energy payback time (without considering a reference system)

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 km² 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.

1 GENERAL

1.1 Introduction

In the forthcoming decades, the world faces a number of challenges:

In the year 2030 more than 8 billion people will presumably inhabit the earth compared to some 6 billion in the year 2000 [UN 2002]. Though, EU population will probably not increase significantly or may even decrease according to projections of [IIASA 1999] for EU-15 countries with a time horizon of 1995-2050. In the past, world energy demand developed in conjunction with the world population.

First signs regarding the scarcity of natural resources will emerge, above all in the field of oil and gas resources. This topic is discussed in more detail in chapter 1.2.

The pressure on the environment has to be lowered in a number of fields. Regarding the production of energy these are predominantly air emissions such as CO_2, SO_2 and VOCs, but also the production of nuclear waste. Renewable energies[1] eventually seem to be the only viable and environmentally benign sources of energy.

Since the 1960ies, great progress were made in the fields of solar energy and space technology. In the year 1968, Dr. Peter Glaser for the first time presented his vision of supplying the world with solar energy from space. Outside the earth's atmosphere solar irradiation is significantly higher compared to the earth's surface. The energy may be transmitted to Earth by means of a laser or microwave beam. Since then, Glaser's vision was further promoted and assessed by all major space agencies.

As sketched in Figure 1-1, an energetic advantage of about a factor four remains in favor of space based solar power systems (SPS), when taking average figures of all relevant processes.

1 "Renewable energies" are any type of useful energy which conversion complies with the basic sustainability rules as stated by e.g. [Enquête 1998].

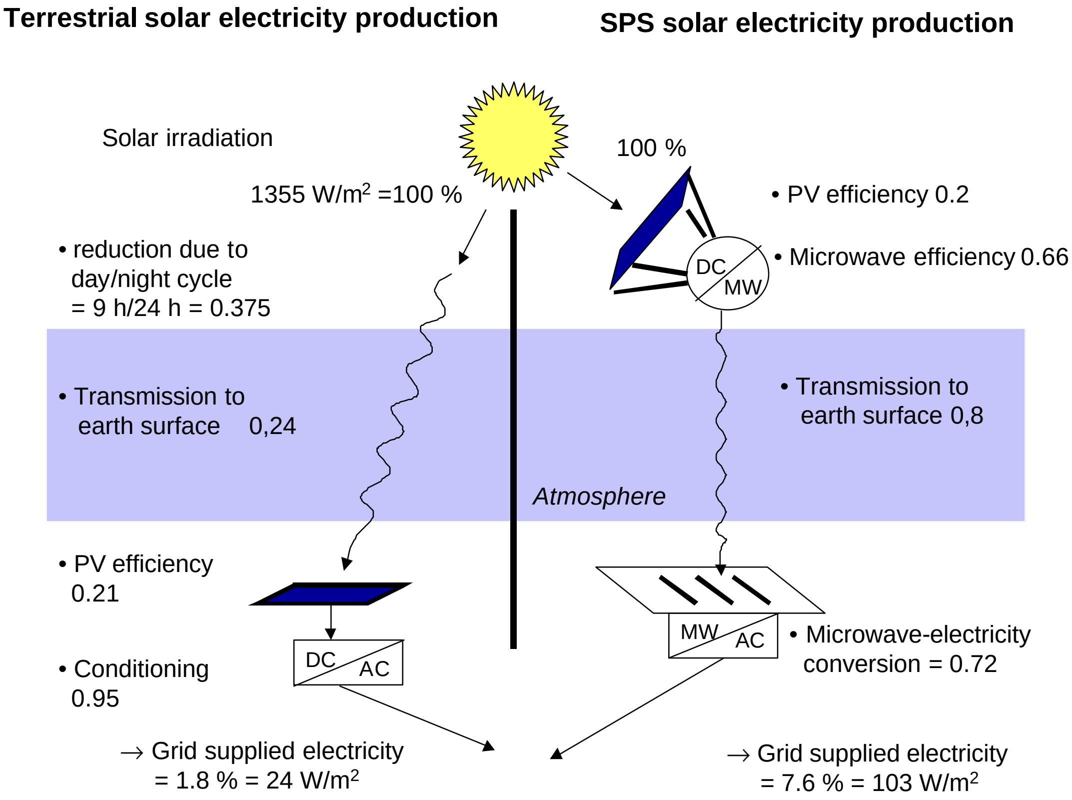


Figure 1-1: Efficiency of solar electricity production from Space and on ground; estimated conversion efficiencies are extrapolated for the year 2030

That tremendous energetic advantage has fed the hope that space based solar electricity production could become a viable energy source in future if problems are overcome, and formed the basis for efforts to produce solar electricity for terrestrial applications in space. In early days, when photovoltaic panels were quite expensive, considerations like that resulted in the rough conclusion, that SPS could become competitive as long as all space related issues other than the PV modules are not more than four times as expensive as the solar modules.

Progresses were made in the field of space based power production from solar energy. The feasibility of basic technologies – such as power transmission via laser or microwave beam – could be proven in principle. Further challenging tasks still lie ahead, such as reducing the launch costs by about two orders of magnitude.

At the beginning of the 21st century, space based solar power generation systems have reached a stage at which a comparative assessment to terrestrial solar power systems became a prerequisite to decide whether to accelerate the development of space based solar power technology (Phase II of ESA Advanced Concepts Team, "Solar Power From

Space – European Strategy in The Light Of Sustainable Development" programme). Two groups were appointed to conduct a study in parallel with the same research goal. The goal of this study is to comparatively assess on a technical basis 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.

For a well defined comparison, the systems are chosen with well defined boundaries:

– Electricity supply of a certain power level or annual energy content to an already established grid completely from space at the one hand, and

– Electricity supply of the same power level or annual energy content to an already established grid completely from terrestrial solar power plants at the other hand.

To take care of industrial learning effects, power sizes of between 0.5 GW and 500 GW are investigated for this analysis.

Pro's and Con's of terrestrial and space based solar power systems are diverse: While SPS seem to be predestinated to provide either base load power or power 'on demand' (i.e. real peak load), the fluctuating nature of the terrestrial solar energy flux requires either a complementing mix of renewable energies (e.g. wind, biomass), storage facilities or further markets (such as clean fuel). The influence of the different nature of these aspects was addressed by splitting the comparison into two complementary analysis. Thus, base load power supply and non-base load power supply were considered apart from each other in respective scenarios.

1.2 Driving forces

Another question concerns the rising pressure to change to a new source of energy "production". The two driving forces behind are technological attractiveness – which usually is reflected in the economics – and resource restrictions, where the latter has the two components resource for sink products (e.g. green house gases) and resource for initial supply.

Greenhouse warming is a well accepted fact within the scientific community and the knowledge is broadly accepted and published (e.g. [IPCC 2001]). This is not the case with the fact that world oil production is close to its maximum and possibly will decline already in the very near future [BGR 2002] [RaymondJames 2004].

Due to the depletion of elder fields and our economic principles, year by year the situation smoothly changes: The finding of new economically exploitable oilfields is continuously shrinking while at the same time old oil and gas fields deplete and have to be substituted by ever more and smaller fields. These in turn start to deplete even faster and to contribute to this treadmill at accelerating time scales, sometimes already in the year after their completion. [Simmons 2002] [EXXON 2002] [LBST 2003]

These facts in background, the growth of oil production is continuously slowing down: Largest growth rates of about 7 – 8% annually were common in the last century until the first oil price shock in 1973. At that time only a few people realized that this growth would never be repeated again. Looking back, between 1973 and 2000 the average growth rate was about 1.5%. One of the reasons was that by far the worlds largest producer for a long time – the USA – had passed its production maximum and turned into decline in 1971. When this happened new field exploration and exploitation first had to substitute for the declining production in the USA before they could contribute to further increases of total production.

Since about 2000 we have entered a new phase: There are only very few regions left where oil production could still be increased. A decreasing number of regions have to compensate an increasing number of regions which have already passed peak production.

Most of the companies have merged to increase their production and reserves, but the world as a whole has experienced a production decline in 2001 and 2002. Over the last two year the production rose again. This results in an average growth rate of about 1 percent since 2000. This and additional signs more and more lead to the conclusion that the world is very close to its oil production maximum. In parallel, companies are investing ever more money in order to sustain present production levels as can be learned from Figure 1-2 and Figure 1-3.

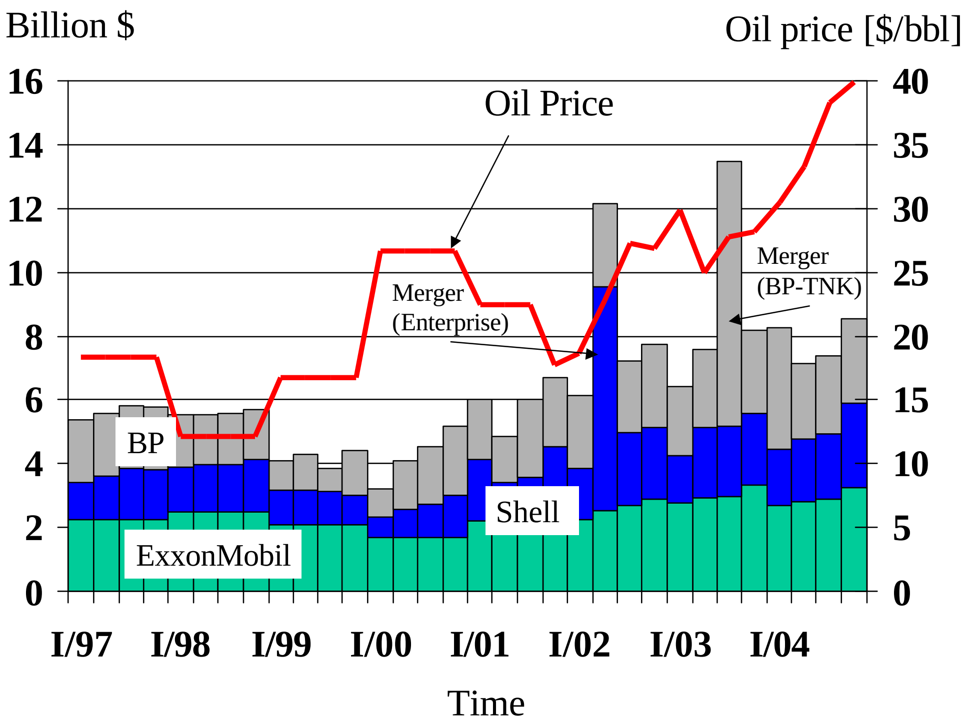

Billion $
Oil price [$/bbl]
Oil Price
Merger
(Enterprise)
Merger
(BP-TNK)
BP
Shell
ExxonMobil
16
14
12
10
8
6
4
2
0
40
35
30
25
20
15
10
5
0
I/97
I/98
I/99
I/00
I/01
I/02
I/03
I/04
Time

Figure 1-2: Company expenditure for exploration and production of the three largest western private companies ExxonMobil, Shell and BP (LBST data derived from quarterly company reports)

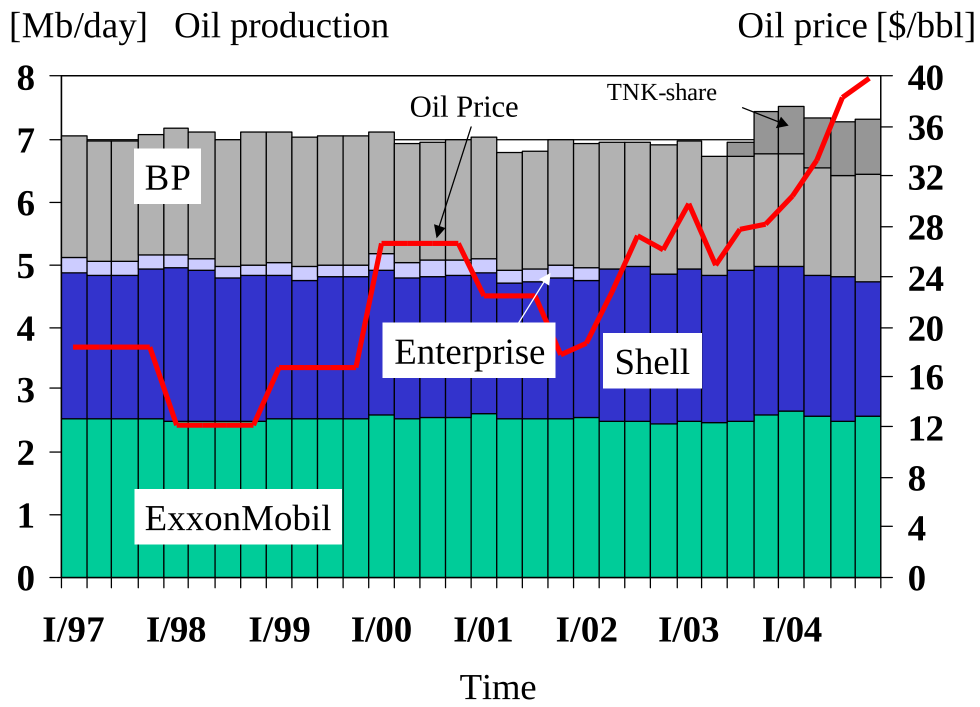


Figure 1-3: Daily oil production of the three largest private western oil companies ExxonMobil, BP and Shell; The increase in spending since 2000 is not accompanied by an increase in production; Additional spending is required in order to keep production at its level; Only the latest deal BP-TNK – worth $ 5 billion – resulted in additional production capacity; It appears to be cheaper to buy production capacity from rival companies than exploring new oil fields (LBST data derived from quarterly company reports)

As soon as people realize the possible consequences of the situation a structural change will set in. New investment will preferentially go into new emerging markets instead of old shrinking ones.

This could be a major driver for a fast expansion of solar electricity production, and, observing the market positioning of large oil companies, it is very likely that they are already preparing for this new situation (BP Solar, Shell Solar, Shell Hydrogen etc.).

1.3 Approach and methodology

This study is based on literature surveys and own calculations only. Practical work – such as experiments, lab work or demonstrations – were not in the scope of this comparison study. Two independent consortia – one lead by L-B-Systemtechnik GmbH (Ottobrunn, Germany) and the other by Ecofys bv (Utrecht, The Netherlands) respectively – were working on the same research tasks. In the course of each group's study, joint workshops were held at defined project stages at the ESTEC's premises in Noordwijk/The Netherlands for a professional exchange. The first workshop took place on 12th and 13th January 2004 and dealt with the work packages I and II. Both groups presented their approaches to the design of the system architecture and scenarios. Both parties involved exchanged their approach and together with the customer jointly agreed upon basic assumptions, such as efficiencies and technology costs (see chapter Basic definitions and assumptions on page 1-26). The second workshop took place on 22nd and 23rd March 2004. The conclusions of work package I and II as well as methodology and preliminary results of WP III and IV were presented and discussed.

In the following paragraphs, the study structure and approach is presented in brief for the sake of methodological transparency:

Chapter 2 'Solar technology' describes fundamentals of terrestrial solar conversion technologies, namely photovoltaics and solar thermal power plants. Additionally, a brief introduction on PV technology for space application is given. Finally, the most promising technologies are selected for implementation into scenario calculation.

Analogue to chapter 2, an overview is given in **chapter 3** 'Space system architectures' over the principle concepts and technologies of space-based solar power systems. Studies in the field are presented and compared. Appropriate concepts for scenario application are then selected and further discussed.

In preparation to scenario calculation, basic assumption and system design issues are discussed in **chapter 4**, such as the geographical scope of the study, terrestrial solar potentials in the target countries, future power demand, limitations of the European transmission grid, appropriate technologies for large-scale energy storage etc.

Based on technology scenario design assumptions as defined in chapters 2 to 4, a base load operation regime is calculated in **chapter 5** for continuous power production of 0.5 GW, 10 GW, 50 GW, 100 GW and 500 GW respectively from solar thermal and space-based solar power plants respectively. The cost of space transportation has been kept parametric in order to determine the average break-even costs for space transport. To compare terrestrial and space-based solar power systems, average costs for mass transport to space are derived in chapter 7.

Analogue to base load scenario calculation in chapter 5, a non-base load operation regime is calculated in **chapter 6**, again without assuming costs for launch. These costs are derived in chapter 7 likewise.

In the course of **chapter 7**, results derived from scenario calculations in previous chapters 5 and 6 are taken into account to determine the average target costs of space transportation.

Up to this point of the study, terrestrial (PV / SOT) and space-based solar power systems have been treated separately. In **chapter 8**, potential technological, operational and other synergies of both terrestrial and space-based solar power systems are explored on a quantitative and qualitative basis. Further synergies are also discussed (chapter 8.3.1 REG-MIX, chapter 8.3.2 H2-FUEL, chapter 8.3.3 SPS-SYNERGIES)

The primary energy effort for each scenario's life-cycle is calculated in **chapter 9**. Thereof, the energy payback times are derived. Furthermore, a discussion on implications from possible changes in heat balance are enclosed.

For the overall comparison of terrestrial and space-based solar power systems, risk and reliability issues are discussed in **chapter 10** to complement previous cost considerations.

Finally, results and conclusions from this study are discussed in **chapter 11** as well as critical issues and fields for further research respectively.

The study is complemented by an **Report Annex** where background data and calculations are stated.

1.4 Basic definitions and assumptions

English punctuation is applied throughout the report.

All cost statements in 2003 Euro (EUR_{2003}). Where required, the following exchange rates were applied generally following [ECB 2003]:

1 EUR = 1.0 $ (USD)

1 EUR = 120 ¥ (JYE)

1 EUR = 0.66 £ (GBP)

1 EUR = 1.55 Fr. (CHF)

Costs are accounted regarding the total cost of ownership (TOC). Final specific costs are stated as levelized electricity costs (LEC). For coherence reasons, the following cost parameters were applied in this report:

Operational life time: 30 yr

Interest rate: 6%/yr (for both own and foreign capital)

Installing and operating power production and transmission facilities occupy terrestrial areas. The extend to which land is used and its respective type are specific to various power system architectures. The following categories of land use are defined with their respective costs:

LAND CATEGORY	DESCRIPTION	COST OF LAND USE
EU urban	roof top, facade, noise protection wall (no competition)	0 EUR/(m²*yr)
EU arable	arable land in Europe	10 EUR/(m²*yr)
EU arid	arid land in Europe (such as the Extremadura in Spain)	10 EUR/(m²*yr)
NA	arid or desert land in North Africa	10 EUR/(m²*yr)
SEA	sea cable crossing the Mediterranean and rectenna sites (Atlantic and Mediterranean Sea)	0 EUR/(m²*yr)
ORBIT	space area (opportunity costs)	0 EUR/(m²*yr)

Figure 1-4: Definition of land use categories and costs

Arid or desert areas may from a today's point of view be free of charge. Yet, above stated costs for these areas take into account the market mechanism of demand and supply. If there is a demand for land, someone will want to be get paid for. This assumption may be more reasonable on the European continent with its relatively high population density in contrary to deserts in North Africa. Regarding Africa, the environmentally benign production of energy may become a future export product for which cost of land use shall contribute to the domestic income generation.

We assume that EU areas do not compete in terms of their use for energy production, e.g. PV vs. low temperature solar thermal on roof tops; high temperature solar thermal or rectennae vs. biomass cultivation on agricultural land. Without this assumption, a more holistic approach regarding the overall effects on the political economics (opportunity costs etc.) had to be applied. Such an approach is beyond the scope of this study.

By agreement between the ESA Advanced Concepts Team and the two research consortia, cost for land use is applied only to land areas covered by transmission lines.

1.5 Data validity and certainty

By nature of this comparison study, the validity and certainty of technical, economic, risk and reliability data is asymmetrically distributed among earth and space based solar power systems. All of the terrestrial applications which are examined in the scope of this study have a proven track record and are well underway to commercial viability. Initial technological R,D&Ds of terrestrial solar power systems date back for more than two decades.

On the other hand, space applications considered in this assessment are yet far from practical reality which is required for large-scale orbital solar power production. Some basic space technologies, such as power transmission via laser or microwave beams, are proven on a feasibility demonstration scale. Some basic space technologies do not yet exist, such as a launching vehicle with the required transportation capacity. The space technology with the most profound experience is photovoltaics (PV) for space, though, the feasibility to scale-up thin film technology has still to be proven.

A figure itself cannot reflect this asymmetry of validity and certainty. A proper result thus consists of figures and their respective, qualifying written statements.

This problem was tackled partly by taking the dominant and uncertain factor – namely the launch cost – as a parameter. By a parameterized search that launch cost factor was identified at which the SPS-concept resulted in specific energy cost comparable to terrestrial solar electricity production. Further investigations were addressed to figure out that learning curve for the cost reduction of the launch cost, which would be compatible with the calculated launch cost to achieve economic break even.

1.6 Study scope / scenario design

By nature of feasibility studies within complex systems, selected scenarios are applied to gain knowledge. The influencing parameters considered in this study are necessarily limited regarding the complexity of today's successively liberalized energy economy. The scope of this study within the context of the energy economy is depicted in Figure 1-5.

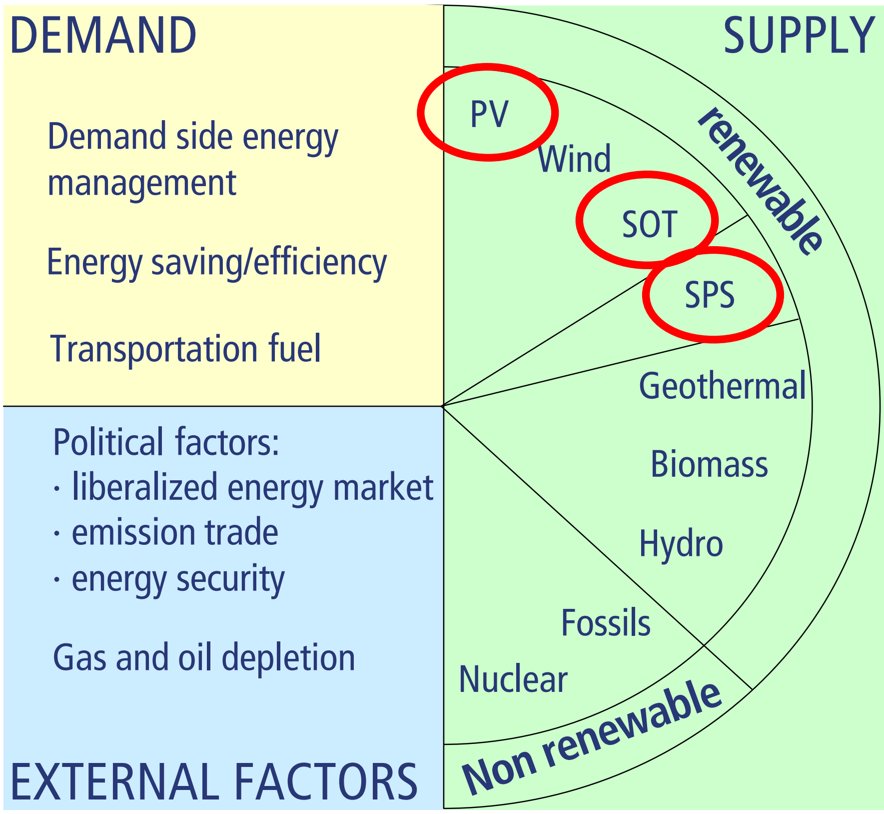


Figure 1-5: Parameters which are marked by a red circle have been considered explicitly in the framework of this study (whether nuclear breeding belongs to the renewable category or not is controversial)

Regarding the scenario design, work package 1 (base load scenarios) and work package 2 (remaining load scenarios) represent the two extremes of possible earth and space based applications of solar power production. These basic scenarios are far from the reality of a divers energy economy. They should not be considered apart from the scenarios assessed in work package 3 (combination of terrestrial and space based power systems) and additional alternative scenarios (mix of renewable energies and hydrogen as transportation fuel). Nevertheless, both work package 1 and work package 2 scenarios may give an impression on the different advantages and disadvantages when applying earth and space solar power systems.

The terrestrial part concentrates on direct solar electricity production only. Due to the fluctuating nature of renewable energy production, the isolation of just one segment is somewhat artificial and does not reflect a development which can be expected to happen over the next decades. Almost any renewable energy technology has its fluctuating primary energy flux pattern. Since these fluctuations are independent between different sources (e.g. wind or hydropower fluctuations are not correlated to the solar flux), any realistic scenario should apply a mix of several renewable technologies, where the share of the individual technologies might be adapted to the regional context. In such a complex scenario the individual fluctuations will interfere and partly compensate each others deficits. This results in a smoothed supply pattern.

Isolating a single technology for such a comparison however requires large efforts to compensate the deficits by storing the supplied electricity for times of preponderant demand.

A fundamental difference between terrestrial PV and space-based solar power systems (SPS) are their different target markets. Whereas terrestrial PV supplies energy to the local power grid (i.e. private consumer market), SPS supplies the high-voltage grid (i.e. bulk power market). Thus, target costs to meet market competitiveness are less stringent for terrestrial PV than for SPS. Yet, in this study for non-base load power supply economic competitiveness with PV are assumed.

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.

These model restrictions should be kept in mind when analyzing the results of the comparison on a single technology level. Nevertheless, such a technological comparison is a first step towards an integrated systems approach and has to be done before more complex models and interactions are studied.

2 SOLAR TECHNOLOGY

2.1 Photovoltaics (PV)

In 2003, about 750 MW_p of PV modules are produced worldwide. The production capacity grew from 560 MW_p (2002) to 750 MW_p in 2003 [Schmela 2004]. Almost 50% thereof came from Japan alone (Europe: 27%, USA: 12.8%).

A broad range of PV technologies coexist at various development stages. Each technology has its specific technological and economic advantages respectively disadvantages. In the subsequent chapters, these technologies are further described in brief. Their potential for today and a possible future (2030) broad scale application is examined as well as critical factors which may hinder their market penetration.

In the course of the first project workshop at ESTEC in Noordwijk/The Netherlands, it was jointly agreed to apply the following key assumptions for terrestrial as well as space PV applications throughout the two consortia:

	TODAY		2030
Efficiency	14 %	Monocrystalline module	21 % Monocrystalline module
	8 %	Thin film module	15 % Thin film module
	-	GaAs technology not applied in short-term	20 % GaAs module
Learning curve start	4,500 EUR/kW_p	Poly and mono crystalline system	
Learning curve factor	20 %	Poly and mono crystalline system cost decrease when doubling installed capacities	

	TODAY		2030	
Learning curve start	4,500 EUR/kW_p	Terrestrial thin film system		
Learning curve factor	20 %	Terrestrial thin film system cost decrease when doubling installed capacities		
Cost space modules			25 %	Cost decrease compared to terrestrial thin film modules

Table 2-1: Basic assumptions agreed upon by both consortia

2.1.1 Technologies

A number of different types of commercial solar cells exist so far: solar cells made with silicon (Si), GaAs (Gallium Arsenid), CdTe (Cadmium Telluride) or CIS (Copper/Indium/Selenium). The market share and the historical development of different PV cell technologies is depicted in Figure 2-1.

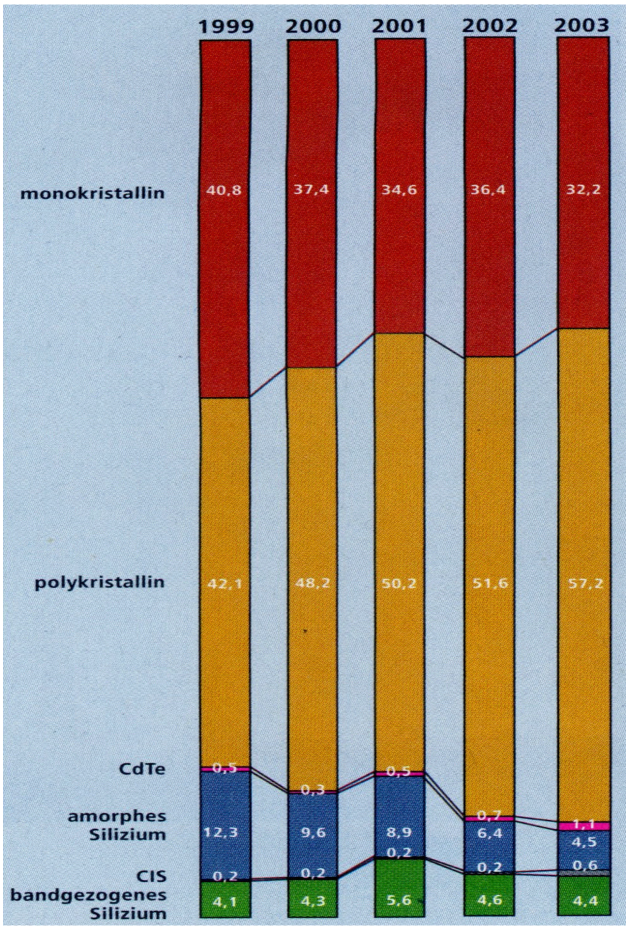


Figure 2-1: Share of PV cell technologies applied worldwide in % [Schmela 2004]

In 2003, more than 90% of the solar cell market production were solar cells fabricated with silicon. Among silicon solar cells, more and more cells are fabricated with multi-crystalline silicon (mc-Si) (57.2%) compared to mono-crystalline silicon (c-Si) with 32.2%. Thin film solar cells are mainly made in amorphous silicon (a-Si) (4.5%).

CIS solar cells which have a share below 1% are by far more successful than CdTe solar cells. This is due to the fact that cadmium was partially banned by Europe, and CdTe solar cells don't have advantages compared to CIS solar cells. CIS solar module production is less mature than a-Si solar module production. However, experts point out that CIS solar modules have a high potential compared to other thin film cell technologies because of their proven high solar cell efficiency with a record breaking 18.8%.

Crystalline silicon cells show a proven record efficiency above 27%.The highest efficiency above 30% has bee achieved with a GaInP/GaAs/Ge tandem-cell. Still higher efficiencies above 35% are achieved with concentrating systems. This topic is also briefly sketched below.

a) Cell and Module

The production of solar cells is akin to the manufacturing of semiconductors. Similar production processes are applied, especially with the production of thin film solar cells (sputter, gas deposition etc.). However, in contrary to semiconductor industry the requirements on material quality are by far less restrictive. Semiconductor manufacturing is based on highly sophisticated production technologies enabling complicated electronic processes at smallest scale. PV cell manufacturing has the opposite goal of producing largest scale with moderate material requirements. By now, the manufacturing technology of solar cells is not yet optimized to reach that goal with the highest efficiency. The potential for further cost reductions is still large. Future cost reductions are expected from enlarged production volumes.

A solar module consists of a number of solar cells which are connected in series/parallel and finally encapsulated. The performance decreases from solar cells to module production because current and fill factor are loosen in solar cell connections and often after encapsulation (less light). Therefore, efficiencies differ depending on whether a solar cell, mini-module or module production is considered.

The ambient conditions, under which a module will be operated, also determine the connections and encapsulation type, which will be different whether solar modules are operated in space (e.g. GEO or LEO orbit) or on earth (e.g. on a boat or on a Swiss or Saharan roof).

- Theoretical limits of solar cell efficiency

Figure 2-2 shows the solar spectral irradiation with respect to the wavelength of the emitted photons. This spectrum is very close to the theoretical thermal radiation spectrum of an ideal black radiator with a temperature of 5,762 K. Therefore that temperature defines the suns radiation spectrum. The overall efficiency of a solar cell is the higher the better its specific band gap matches with the spectrum of radiation.

These introductory considerations explain major factors influencing the efficiency of a solar cell. However, a detailed discussion has to consider additional effects, e.g. the solar spectrum which is distorted by the atmosphere which has an influence on the efficiency curve.

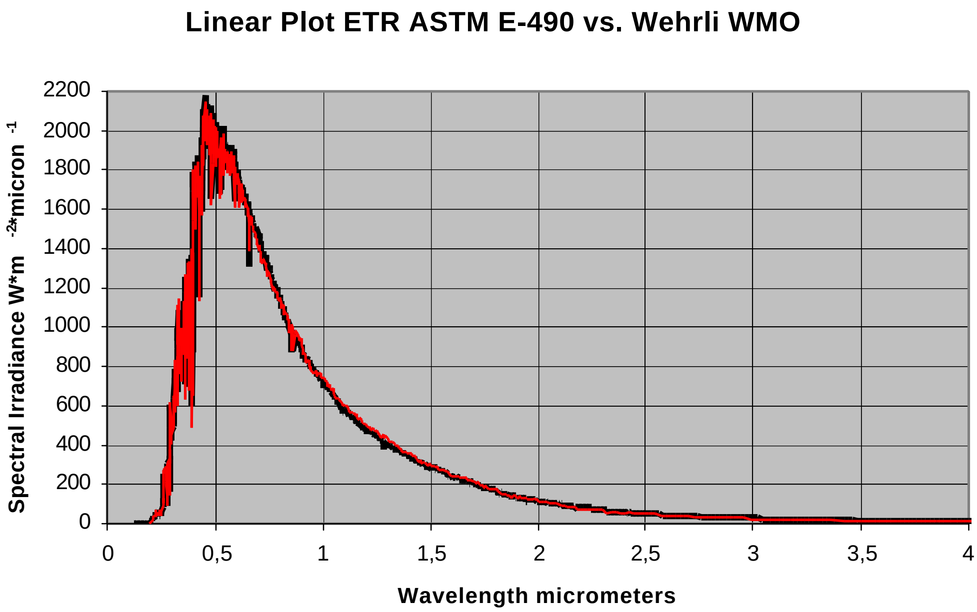


Figure 2-2: Solar spectrum measured in space at AMO [Smith 1974]

Only those photons from the solar spectrum can initiate electric currents within a semiconductor whose energy exceeds the band gap of the semiconductor under investigation as explained in Figure 2-3. If an electron receives the energy $E>E_{gap}$ it can escape from its fixed location and move around (in technical terms: the electron is shifted from the valence band to the conduction band).

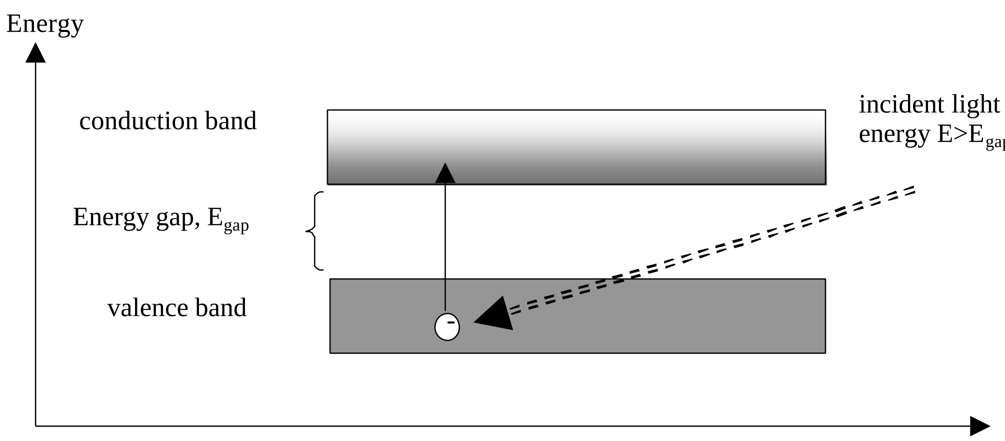


Figure 2-3: Energy gap of a semiconductor and energy transfer from incident photon to electrons

It can return to its initial location either by spontaneous recombination – which usually is the case in pure semiconductors – or via a conductive wire and produce electricity. A solar cell is optimized in a way that the excited electrons move away before spontaneous recombination may occur. This movement is forced by the intrinsic electric field in the transition regime of a p/n-diode as sketched in Figure 2-4.

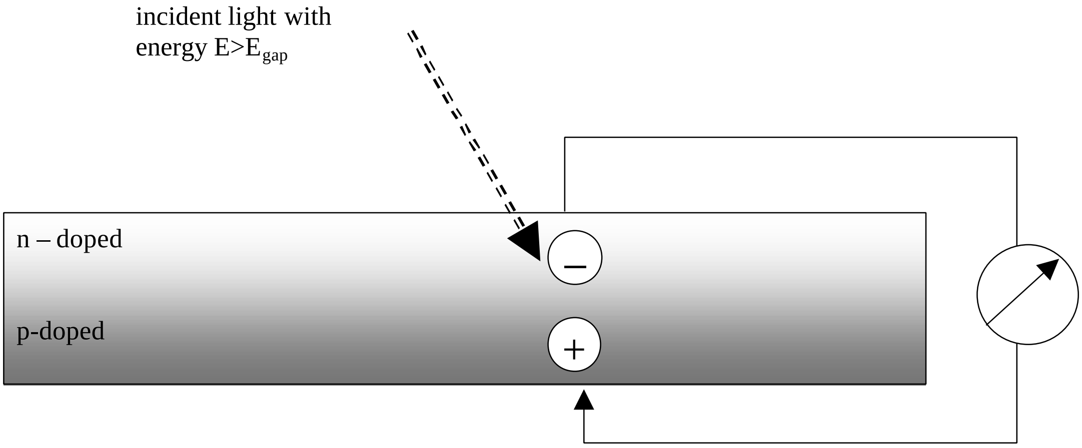


Figure 2-4: Schematic cross section through a solar cell. The light penetrates the solar cell. Photons with a higher energy than the band gap may excite electrons in a way that a pair of electron/hole is generated. The intrinsic field pushes the electron away from the transition zone between the p- and n-doped layers. A recombination is thus avoided. The electron then makes its way through the external circuit where it may be measured as an electrical current.

The band gap E_{gap} of any semiconductor corresponds to a certain wavelength of the photons. For instance, for silicon, any photon with wavelength below 1 micrometer can excite an electron into the valence band. Consequently, each photon with wave length larger than 1 µm heats up the semiconductor or passes the semiconductor without collisions, but cannot contribute to electricity production. Therefore, the lower the band gap, the more electrons can be excited to produce electricity. But on the other hand, each electron in the valence band can contribute to electricity production only with the fixed energy amount of the band gap, E_{gap}. The Energy amount of the photon with $E>E_{gap}$, again, is converted into heat not contributing to electricity production. These two parameters determine that only a certain amount of solar radiation can be converted into electricity: Just because only part of solar photons contributes to electricity production, and from these photons only a certain energetic fraction is converted into electricity. Beyond these basic principles, additional restrictions limit the efficiency even further:

1. Not every photon which hits the semiconductor, transfers its energy to the electron.
2. Inside the semiconductor, an electrical field builds up. A certain fraction of electrons tends to recombine before it can be removed from the remaining ion. Once too many

electrons are excited into the valence band, spontaneous recombination starts which again reduces the amount of electrons, which take the bypass through the conducting wire.

3. The ambient temperature of the semiconductor has an additional influence on the ability of spontaneous recombination or excitation.

Putting all aspects together results in a (slightly simplified) theoretical maximal conversion efficiency depending on the band gap of the solar cell as shown in Figure 2-5. At best 30% of the incident light energy can be converted into electricity with a semiconductor with band gap of 1.25 eV. Any deviation from this figure further reduces the efficiency.

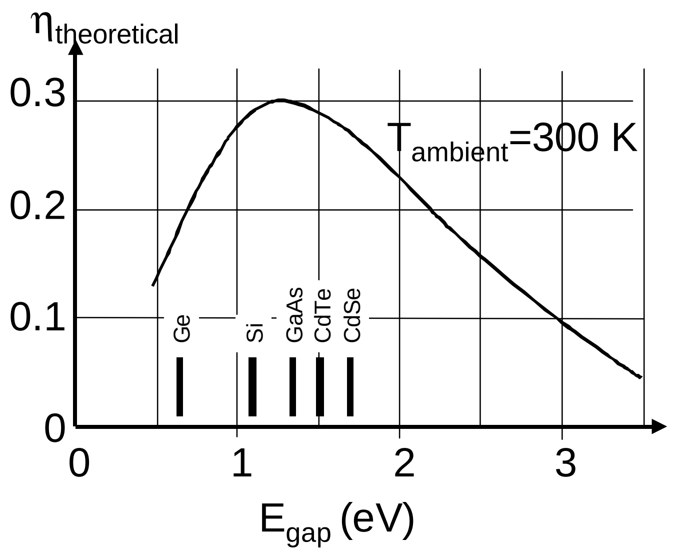


Figure 2-5: Theoretical maximum efficiency of a solar cell depending on its band gap energy. This efficiency curve is adapted to 300 K cell temperature and AM0 spectrum (solar spectrum in space). Only multi-junction cell can exceed this figure.

These theoretical figures are further diminished by geometrical constraints. Only a certain fraction of light is absorbed within a fixed distance. The thicker the material, the more photons are absorbed, and vice versa, the thinner the cell, the less photons are absorbed and the efficiency reduces corresponding to the absorbed fraction. This is the major reason behind the low efficiencies of thin film cells. By light reflection at the back side the light absorption and consequently the efficiency can still be enhanced.

The efficiency can still be increased by several measures, e.g. by means of double junction and multi junction thin film solar cells. An increase of the solar flux density by concentration also raises the efficiency. The best results are achieved when different cells with different band gaps are used and the incident solar spectrum is split directing each segment of wavelengths towards the appropriate cell, e.g. one cell which absorbs high energetic photons and another cell which absorbs low energetic photons. Since the not absorbed photons penetrate through the cell without interaction, these two cells can be build above each other (sandwich concept). The more the solar spectrum is split and directed to its corresponding cell the higher is the conversion efficiency, partly compensating for the low absorption of thin films.

- Thick Film: Single-crystal (mono-Si) and poly-crystal (poly-Si) silicon cells

Thick film solar cells are by far the best investigated solar material where most experience and best knowledge exists. 92% of the production volumes are silicon based solar cells, with the majority being crystalline thick film cells. This, of course, is due to the broad experience which was already gained within the conventional semiconductor industry. Another fact is that these cells may be produced from semiconductor material of lower quality. The semiconductor industry is thus the major supplier of today's silicon feedstock for PV cells. This synergy facilitated the introduction of silicon PV technology in terrestrial markets. At the other hand, the application of semiconductor byproduct as feedstock is a constraint towards cheaper cells. These will be based once the crude material, the crystalline silicon, is produced exclusively for the solar market, since the requirements are considerably lower than on silicon used by the semiconductor industry. In recent years, more and more the silicon cell was reduced to smaller thickness. Starting with some 250-300 µm, researchers reduced the size to 150 µm with improved saws. The increasing market of the last years has helped to address the problem of reducing material requirements further. Smaller silicon amounts are consumed by different growth concepts, where the silicon is not grown from large single crystals with several inches in diameter – as appropriate for semiconductor industry – but with different flow techniques allowing for less material requirement already from the beginning.

The progress in terms of efficiency for silicon thick film cells and the whole module are given in the following Figure 2-6.

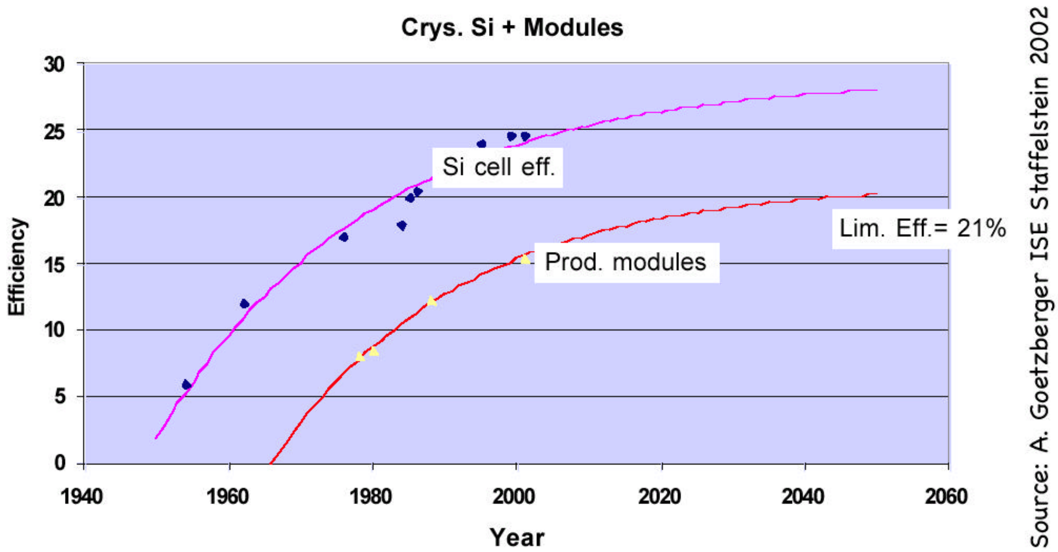


Figure 2-6: Development of the efficiency of silicon solar cells and modules [TNC 2004]

- Thin film

Thick solar cells (300 µm) are fabricated mainly with mono or multi-crystalline silicon (Si) and GaAs for space applications. These solar cells are heavy, fragile and expensive. The thickness is determined by the cut limit of the Si ingot and not by the optimum thickness it requires to absorb the maximum of the solar spectrum. Therefore laboratories are looking for thinner solar cells in order to decrease the raw material quantity, decrease the production price and make it flexible. Today, two approaches exist:

1. Further rely on multi or mono crystalline silicon and make it thinner or fabricate it with epitaxy technology
2. Use of other material and production technologies such as a-Si, CIS or CdTe material.

With reference to the first approach: If it is possible to obtain 16% of efficiency for a solar cell. However, the required technologies are very expensive which up to now prohibits their production.

In the second approach there are three kinds of materials which are considered: silicon – but in a different phase than mono or multi silicon (so called "thin film silicon") –, CIS and CdTe. These three solar cell technologies may be produced by applying cheaper production technologies than multi-crystalline silicon solar cells. Furthermore, thin film solar cells may be deposited on a flexible substrate.

The following chapter specifies the differences of thin film silicon, CIS and GaAs solar cells.

Thin film silicon

Thin film silicon may be deposited in many ways. The most common one is the PE CVD method (Plasma Enhance Chemical Vapor Deposition). Thin film silicon solar cells are deposited between 100°C and 300°C. The manufacturing temperature allows the possibility to use polymer substrate. With this method it is possible to obtain a silicon layer more or less crystallized. The crystal quality ranges from amorphous – which contains no crystals – to microcrystalline – which contains small crystals. These materials allow to add germanium or carbon atoms in order to enlarge thin film silicon properties: a-Si Ge has a smaller gap energy than a-Si and a-Si has a smaller gap energy than a-Si C. It is thus possible to compose multi-spectral solar cells as shown in Figure 2-7 and Figure 2-8.

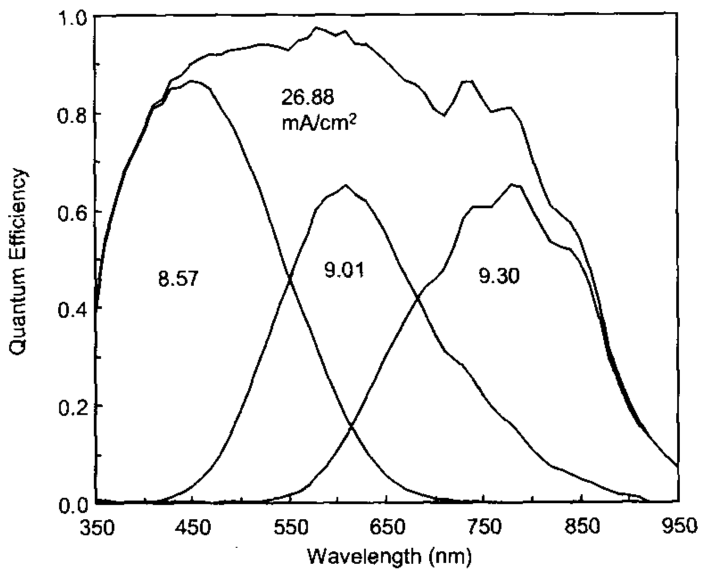


Figure 2-7: Combined energy yield of a triple junction, thin film solar cell under standard test conditions[2] [Yang et al. 2003]

2 PV standard test conditions (STC): Solar irradiance 1,000 W/m², reference air mass (AM) solar spectral irradiance distribution 1.5 and cell/module junction temperature 25°C

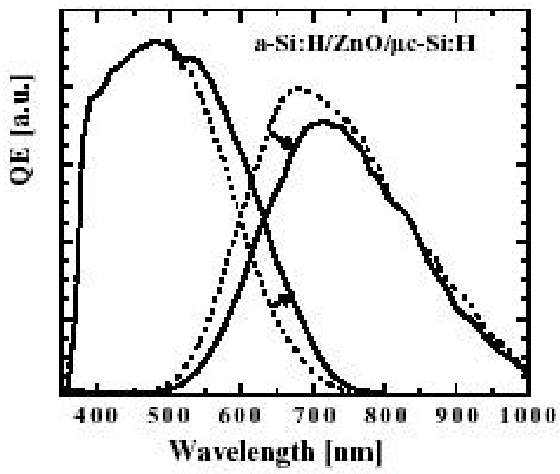


Figure 2-8: Quantum efficiency of a micromorph solar cell which consists of an amorphous silicon solar cell and a microcrystalline silicon solar cell. These two materials have two different band-gaps [Meier et al. 2003]. This solar cell has a stable efficiency of 10.8%.

In contrary to poly-crystalline PV cells, degradation caused by light soaking occurs fast and is higher with amorphous silicon cells. According to [Yang et al. 2003] stable overall efficiencies are larger than 9% with single junction, larger than 10% with same gap double junction, larger than 12% with dual gap double junction and ~13% with triple junction amorphous silicon cells.

Thin film PV cells have the potential to be produced in a continuous manufacturing process. Yet, further developments regarding the process design have to be made to achieve high quality layers at a high throughput. This is the prerequisite to lower the costs of amorphous silicon PV cell production. [Yang et al. 2003] suggests a roll-to-roll manufacturing process as denoted in Figure 1-2. The film may then be cut into the size required by the final product.

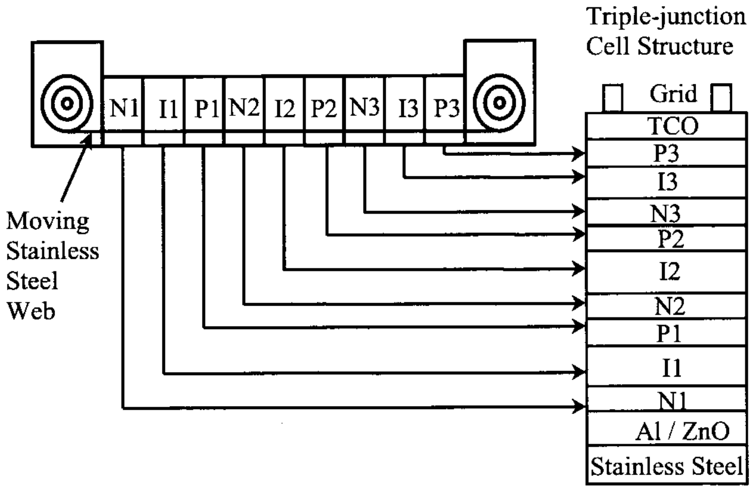


Figure 2-9: Schematic diagram of an industrial process for the in-line production of triple-junction, thin film solar cells [Yang et al. 2003]

In the year 2001, worldwide sales of amorphous silicon modules amounted to 34 MW. Though, amorphous silicon modules still account for less than 10% of the total PV market worldwide [Yang et al. 2003].

CIS / CIGS

Chalcopyrite compounds belong to the group of I-III-VI2 semiconductors. Typical absorber materials are $CuInSe_2$, $CuGaSe_2$, $CuInS_2$, and alloys thereof with band gaps ranging from 1.05 eV to 1.7 eV. The preparation of absorber layers for high efficiency CIGS devices includes a manufacturing step at a high process temperature (500°C). Considering a flexible device, this puts some constraints on the substrate. Nevertheless, it could be proven that working hetero-junctions can be processed from absorber layers applying deposition temperatures at 310°C, albeit with losses in efficiency [Flexis 2001].

The current record efficiency is 18.8% for a solar cell using a $Cu(In,Ga)Se_2$ alloy [Contreras 1999].

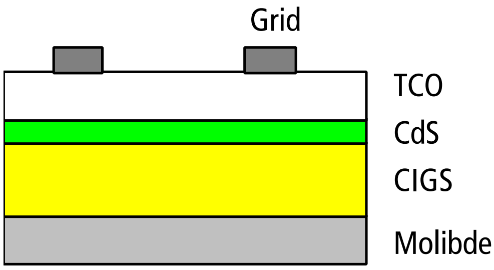


Figure 2-10: CIGS solar cell comprising a back contact made of Molibden, an absorber (CIS material), a buffer layer CdS, a top contact transparent like ZnO and a metallic grid.

When comparing CIGS with silicon thin film technology, both technologies provide different advantages. The efficiency of CIGS solar cells has always been higher than the efficiency of silicon thin film solar cells as can be seen in Figure 2-11.

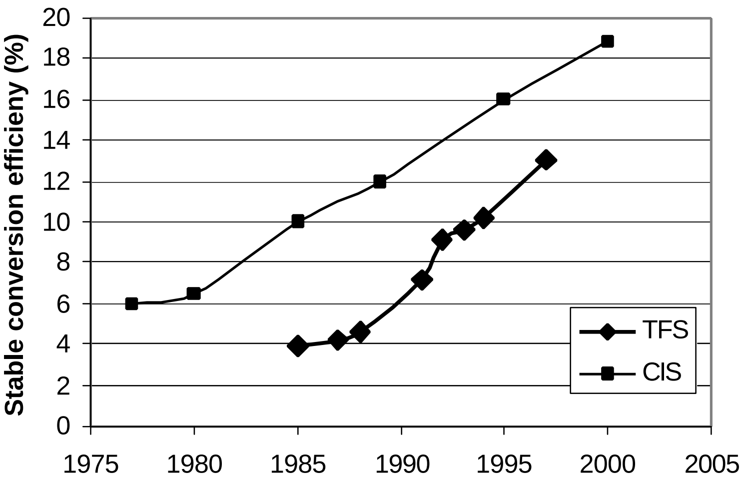


Figure 2-11: Track record of stable conversion efficiencies of thin film silicon and CIGS solar cells based on NREL data

Though the conversion efficiency of thin film silicon is lower compared to CIGS, TFS offers a number of advantages over CIGS:

– Thin film silicon may be deposited at very low temperatures (100°C – 200°C). Thus, it is possible to deposit silicon on polymer substrates as well which is lighter and cheaper than a metal substrate.

– Production of thin film silicon solar modules is simpler than CIGS solar modules.

– Connections between solar cells may be monolithic

Thin film GaAs

These kind of thin solar cells (3 µm) are deposited on thick GaAs wafer (200µm – 300µm). Efficiency may exceed 30%. Yet, they are very expensive and complex to manufacture. Only space agencies allow the development of these solar cells. There is yet no market for terrestrial applications for GaAs solar cells except for use in concentrating systems as sketched below.

Thin film for space applications – Degradation

In 1987 the LIPS-III mission carried three $CuInSe_2$ cell strings provided by Boeing. After 965 days in space the performance of non-encapsulated CIS-cells dropped by as little as 4% – 7% [Burgess 1993].

In 1998, Uni Solar sent on MIR station thin film silicon solar module with 7.5% of efficiency, covered with 2-3 µm of SiO_2. After 225 days there were no degradation. Parallel tests were done which showed that solar cell efficiencies decrease drastically under proton and electron degradations with low energies but after annealing (70°C) efficiencies are recovered. In fact, in space, on MIR station, module temperatures have been estimated at 70°C [Kagan 2000].

In 2000 NASA sent CIS module with 2% of efficiency (4''x4'') composed with solar cells with efficiencies close to 10%. But current dropped and after 3 months there was no current at all. They suspect connection problems [Carpenter 2001].

Flight data of CIGS and GaAs at the EQUATOR-S experiment [Messenger 2001] confirmed the strong radiation hardness of CIS solar cells. The recorded degradation of CIS cells was one order of magnitude smaller than GaAs cells. A displacement damage dose analysis performed to predict the degradation history of the investigated cells showed good agreement between modeled and recorded data.

Many experiments, like proton and electron irradiation, was done on thin film solar cells. Conclusions are often the same: thin film solar cells are more resistive than thick solar cells (c-Si and GaAs) in same conditions. But if thin film solar cells resistance is higher under high proton energies it is not the case under low proton energies. But thin film solar cells recover their properties after annealing.

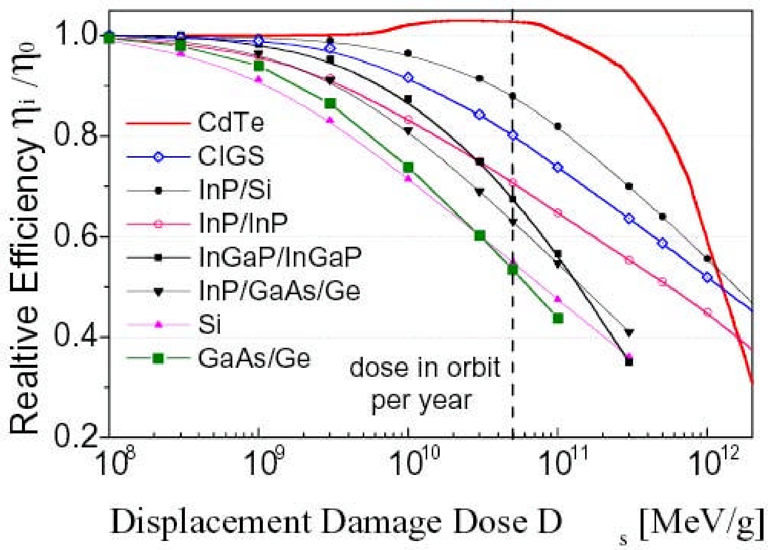


Figure 2-12: Efficiency degradation curves of thin film solar cells under various space conditions in terms of radiation intensity [Ott 2004] Ott, H.: Thin Film Cells for Solar Applications, www.tfp.ethz.ch/SpaceApp/SpaceApp.html, as per April 6, 2004

In 2006 the US schedule the launch of TechSat 21. USSC (Uni Solar), Global solar and DayStar modules will be launched in this mini-satellite the by Air Force. USSC says: 'This developmental program is aimed at producing modules which can generate more than 2000 W/kg at 10% efficiency' (they obtained already 1,250 W/kg).

There are some differences between terrestrial and space solar cells due to environmental conditions. In space there is no oxygen but proton and electron irradiations. There is no atmosphere, so pressure is much lower than on earth. Temperature variations are very important (often between –100°C and +100°C depends on the orbit). Main problems occur on glass and solar cell degradations (particle irradiations) and with connection degradations which is linked with encapsulation.

For thin film solar cells it must be sufficient to cover them with a thin film of SiO_2 to protect them in space whereas strong waterproof encapsulation is necessary to protect solar cells on earth. Furthermore, if these solar modules are installed on building, they must resist at very hard tests like fire and strong hits. Before their launch to space, solar cells must pass tests for space-worthiness (thermal cycle etc.).

Figure 2-13 summarizes achieved "class records". These efficiencies are still exceeded by "notable exceptions", e.g. for CIGS 18.8% are measured at NREL in December 1998, or 31% are reported from NREL for GaInP/GaAs/Ge in October 2000 – in the meantime the latter record is pushed even further. Also not included are concentrating cells.

Table I: Confirmed terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 Wm^{-2}) at 25°C.

Classification[a]	Effic.[b] (%)	Area[c] (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF[d] (%)	Test Centre[e] (and Date)	Description
Silicon Cells							
Si (crystalline)	24.7 ± 0.5	4.00 (da)	0.706	42.2	82.8	Sandia (3/99)	UNSW PERL[3]
Si (multicrystalline)	19.8 ± 0.5	1.09 (ap)	0.654	38.1	79.5	Sandia (2/98)	UNSW/Eurosolare[3]
Si (supported film)	16.6 ± 0.5	0.98 (ap)	0.608	33.5	81.5	NREL (3/97)	AstroPower (Si-Film)[4]
III-V Cells							
GaAs (crystalline)	25.1 ± 0.8	3.91 (t)	1.022	28.2	87.1	NREL (3/90)	Kopin, AlGaAs window
GaAs (thin film)	23.3 ± 0.7	4.00 (ap)	1.011	27.6	83.8	NREL (4/90)	Kopin, 5 mm CLEFT[5]
GaAs (multicrystalline)	18.2 ± 0.5	4.011 (t)	0.994	23.0	79.7	NREL (11/95)	RTI, Ge substrate[6]
InP (crystalline)	21.9 ± 0.7	4.02 (t)	0.878	29.3	85.4	NREL (4/90)	Spire, epitaxial[7]
Polycrystalline Thin Film							
CIGS (cell)	**18.4 ± 0.5**	**1.04(t)**	**0.669**	**35.7**	**77.0**	**NREL (2/01)**	**NREL, CIGS on glass[8]**
CIGS (submodule)	**16.6 ± 0.4**	**16.0 (ap)**	**2.643**	**8.35**	**75.1**	**FhG-ISE (3/00)**	**U. Uppsala, 4 serial cells[9]**
CdTe (cell)	**16.4 ± 0.5**	**1.131 (ap)**	**0.848**	**25.9**	**74.5**	**NREL (2/01)**	**NREL, on glass**
CdTe (submodule)	10.6 ± 0.3	63.8(ap)	6.565	2.26	71.4	NREL (2/95)	ANTEC[10]
Amorphous Si							
a-Si (cell)[f]	12.7 ± 0.4	1.0 (da)	0.887	19.4	74.1	JQA (4/92)	Sanyo[11]
a-Si (submodule)[f]	12.0 ± 0.4	100 (ap)	12.5	1.3	73.5	JQA (12/92)	Sanyo[12]
Photochemical							
Nanocrystalline dye	6.5±0.3	1.6(ap)	0.769	13.4	63.0	FhG-ISE (1/97)	INAP
Nanocrystalline dye (submodule)	4.7 ± 0.2	141.4 (ap)	0.795	11.3	59.2	FhG-ISE (2/98)	INAP
Multijunction Cells							
GaInP/GaAs	30.3	4.0 (t)	2.488	14.22	85.6	JQA (4/96)	Japan Energy (monolithic)[13]
GaInP/GaAs/Ge	28.7 ± 1.4	29.93(t)	2.571	12.95	86.2	NREL (9/ 99)	Spectrolab (monolithic)
GaAs/CIS (thin film)	25.8 ± 1.3	4.00 (t)	-	-	-	NREL (11/89)	Kopin/Boeing (4 terminal)
a-Si/CIGS (thin film)[f]	14.6 ± 0.7	2.40 (ap)	-	-	-	NREL (6/88)	ARCO (4 terminal)[14]

[a] CIGS = $CuInGaSe_2$; a-Si = amorphous silicon/hydrogen alloy
[b] Effic. = efficiency
[c] (ap) = aperture area; (t) = total area; (da) = designated illumination area
[d] FF = fill factor
[e] FhG-ISE = Fraunhofer-Insitut für Solare Energiesysteme; JQA = Japan Quality Assurance
[f] Unstabilized results

Figure 2-13: Confirmed terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum at 1,000 W/m² and 25°C [UNSW 2004]

b) Balance of System

Balance of system (BOS)[3] components mainly comprise power electronics, cabling, support structure and energy storage. Typical lifetimes differ between the different components: Whereas PV cells and modules have at least 20 years of operational life-time, the BOS components (e.g. AC/DC converters) have a lower life time of about 10 years. In addition, since BOS components are more or less based on conventional technologies, learning effects of BOS components due to up-scaling of production volumes are different to those of solar cells and modules. As can be seen from Figure 2-14, actually most of the system cost reduction during the past years is attributable to learning effects in the field of BOS components. These learning effects, however, have a different nature than those achieved with cells and modules. The past learning is mainly based on the shift from individually planned system architectures to standardized systems designs. Further details concerning learning curves are discussed in chapter 2.1.4d).

[3] sometimes also called Balance of Plant (BOP)

The following figure exhibits that the cost degression of the past years was predominantly due to cost reductions achieved with BOS. This helped to increase the relative cost share of the module. Therefore further cost decreases are predominantly expected with the cost degression of the modules.

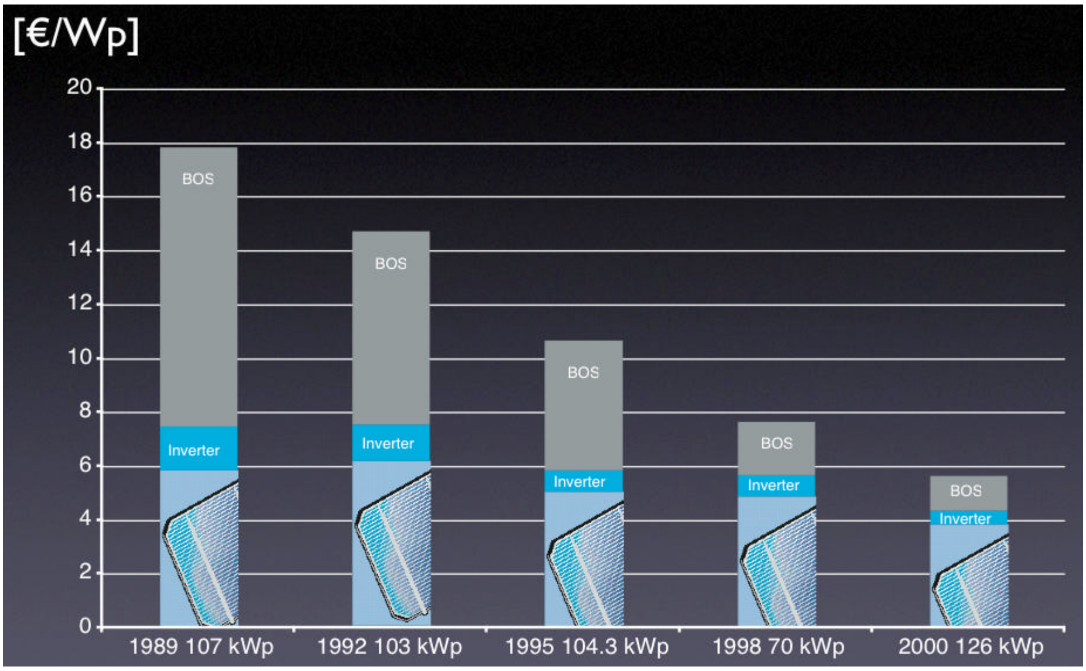


Figure 2-14: PV system learning curve; The total system cost continuously decreased over the last 15 years. However, most of this decrease was due to BOS cost, therefore the relative cost share of the module increased. Further cost reduction will predominantly depend on module cost and its development. [TNC 2004]

2.1.2 System design

Among other system design issues, (partial) shading may be applicable when installing PV systems on roofs, facades and noise barriers.

Partial shading – even with the smallest amounts of area – results in a disproportional loss of PV system's power output [Archer 2001], [Quaschning 1996] and – in the worst case – to so-called hot spot effects. System damage and failures due to hot spot effects are reported e.g. by [Roche 2002]. That is, a reduction of sunlight reaching the PV module by 5% due to shading can cause losses of 30-40%. These losses consist of shading losses – which are proportional to the shaded surface – and so-called mismatch losses which are not proportional to the shaded surface. The system specific degree of power losses depends on several parameters: The PV technology applied (thin film is more tolerant towards partial shading than wafer-based PV modules which is due to the series connection of PV cells); degree and pattern of the shading; the electrical system architecture (namely regarding the connection architecture of the array, inverter and by-pass diode). The impact of patchy shading stretching over the total of the PV module surface – as would be the case with overhead rectennae – is more difficult to handle than a singular large area shading of some modules. Figure 2-15 and Table 2-2 depict the correlation of the type of shading and the type of electrical system design chosen for four scenarios A, B, C and D.

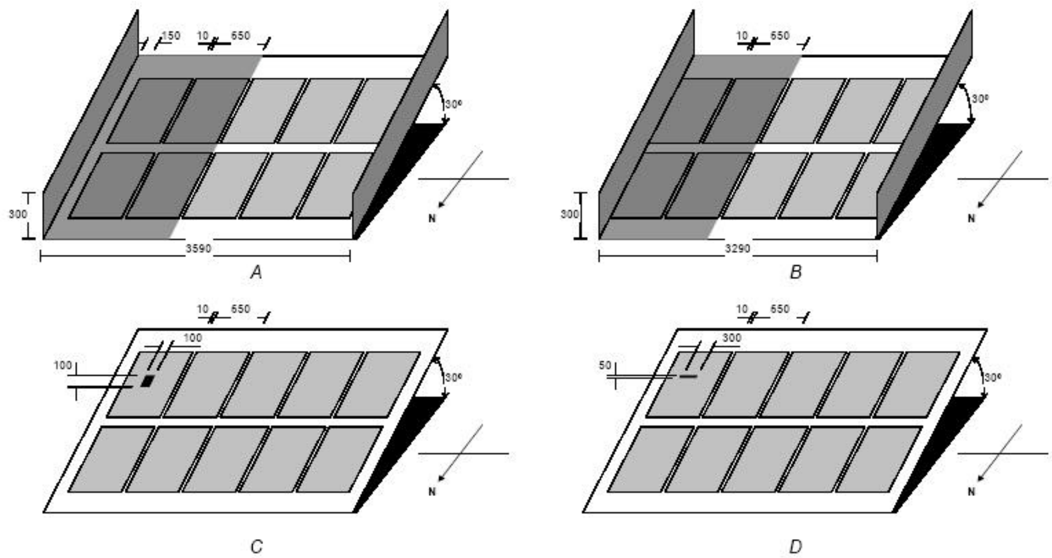


Figure 2-15: System layouts and shading scenarios modelled by [Roche 2002]

scen-ario	system description	annual energy output (kWh/kW$_p$)	shading loss (%)	mis-match loss (%)	total loss (%)
	no shading	1500	0.0	0.0	0.0
A	no mismatch	1460	2.6	0.0	2.6
	module inverters	1420	2.6	2.8	5.4
	central inverter	1338	2.6	8.4	10.8
B	no mismatch	1412	5.9	0.0	5.9
	module inverters	1291	5.9	8.6	14.0
	central inverter	1068	5.9	24.3	28.8
C	no mismatch	1498	0.1	0.0	0.1
	module inverters	1350	0.1	9.9	10.0
	central inverter	1417	0.1	5.4	5.5
D	no mismatch	1497	0.2	0.0	0.2
	module inverters	1445	0.2	3.5	3.7
	central inverter	734	0.2	50.9	51.0

Table 2-2: Results of system modelling showing the impact of partial shading depending on the parameters shading type and electrical system design [Roche 2002]

2.1.3 Concentrating photovoltaic systems

Under concentrated radiation from the sun the performance of solar cells increases. In the new breed of multi-junction photovoltaic cells however, the current increases proportionately to the concentration not the voltage – which is the main element of conversion losses. Because of this, cell efficiencies of over 35% may be reached if the radiation is spread uniformly on the cell by a homogenizing optics [DGS 2005].

Therefore the alternative approach to low electricity cost is a system that concentrates the solar radiation with an appropriate low cost concentrating system in order to save expensive solar cell material, and to enhance the yield by increasing the efficiency.

This is what the "Boeing-Spectrolab-Pyron Solar Generator" addresses. The efficiency of their cells (confirmed by NREL of the DOE) is 37.3%. Further R&D targets to achieve an conversion efficiency of 40% [Laing 2004].

Pyron Inc., a California based R&D company, developed this concentrating system with an extremely short focal length using these cells. A major aspect of their development was the alignment of system components in a shallow water body, separated from the soil by a plastic membrane and covered by a thin film of a hydrophobic liquid to prevent evaporation. The merits are a water bearing for the sun tracking system, water cooling for the cells and exact horizontal alignment of the floating lens holders.

The first prototype has been built in El Cajon, near San Diego California. The platform, 23 feet (~7 m) in diameter and 12 inches (~0.3 m) in height, generates 6.6 kW electrical peak power. At 1,000 W/m^2 solar irradiation, this translates into more than 20% conversion efficiency for the whole system. According to Pyron the annual conversion efficiency (irradiation per square meter/power plant area) for a full plant of, for example 50 kW$_p$ will be about 17.5% [Laing 2004].

Pyron estimate the investment for these plants will potentially be below 2 US$/W$_{peak}$ so that these systems will be able to produce power at similar cost as fossil fuel power plants. The design of a proposed 50 kW$_{peak}$ plant is shown in Figure 2-16.

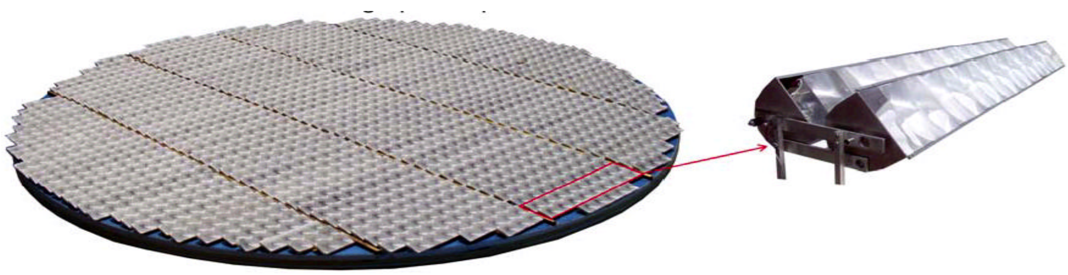


Figure 2-16 Proposed PV plant concept with 50 kW$_p$ power output using concentrating lenses. The plant diameter is 16 m [Pyron 2004]

In the course of this work, a detailed cost assessment with projected cost and life cycle analysis could not be studied due to lack of time. Therefore, the system is only mentioned here as a promising alternative with eventually lowest costs but not used for cost comparisons.

2.1.4 Economics

The current world market for PV modules is mushrooming with annual growth rates > 30% for the last couple of years. The major driver for this success story are national rebate or loan schemes and combinations thereof. A potentially huge 'niche' market is at place where PV technology is already cost competitive to conventional forms of power generation. This market mainly consists of remote and off-grid applications, such as rural electrification. Reportedly, some 2 billion people do not yet have access to electricity [World Bank 1996] [WEC 1999] [APERC 2001]. Today's technology's high up-front investment requirements represent the major hindrance for market entry.

Figure 2-17 gives an overview over the major PV manufacturers worldwide.

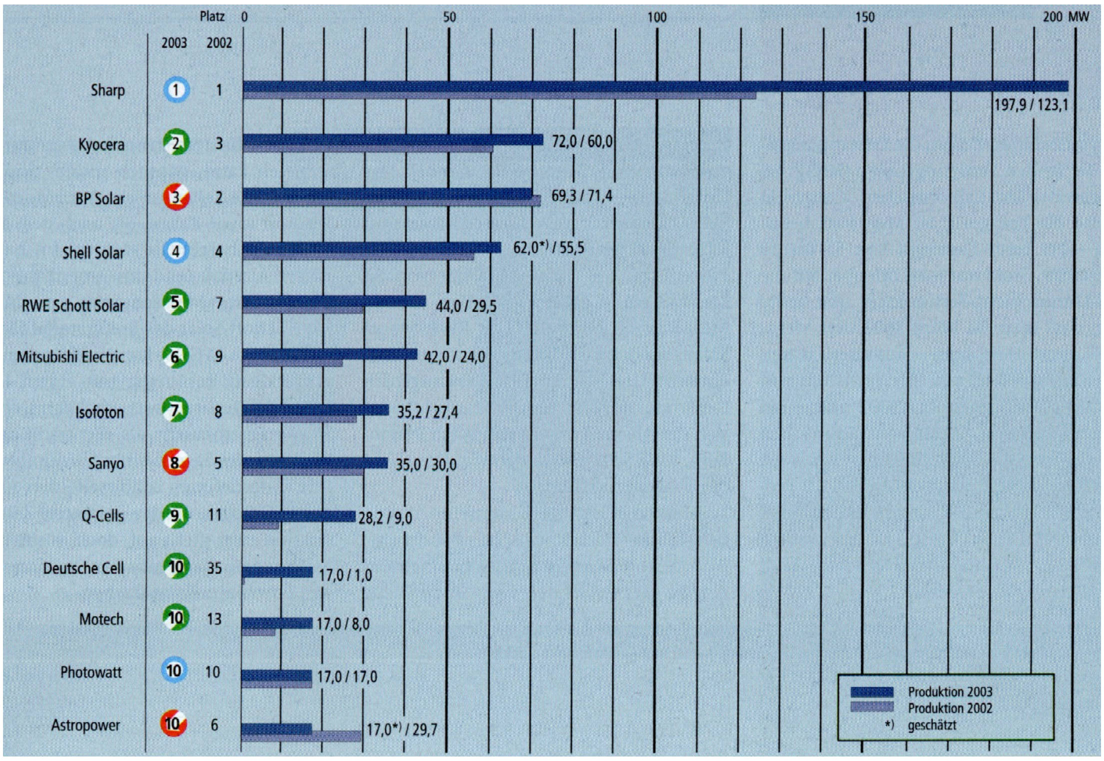


Figure 2-17: PV production by company [Schmela 2004]

Figure 2-18 depicts the share of PV production worldwide by continent. By far the largest single producer is Japan. Europe as a whole follows with a share slightly over 25%.

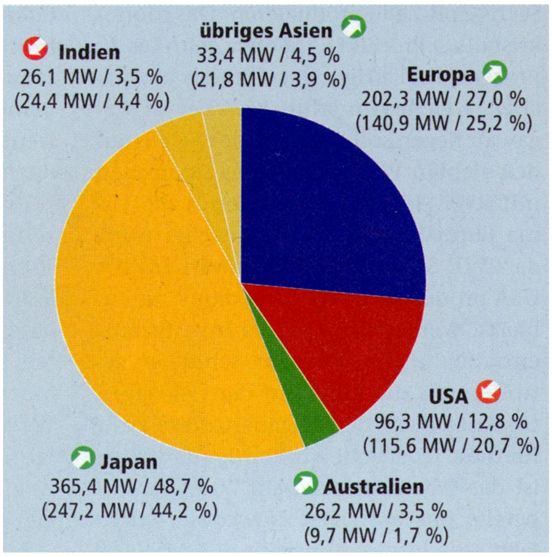
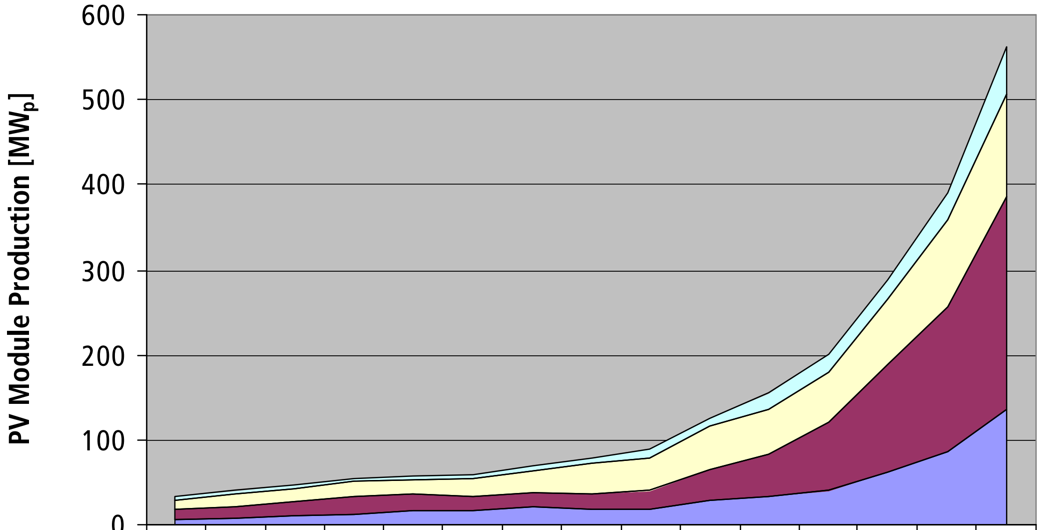


Figure 2-18: PV production by continent. Data are for 2003; 2002 data are in brackets [Schmela 2004]

a) Historical market development

The historical market development and its share of different PV technologies is depicted in Figure 2-19. The cumulated production volume between 1988 and 2002 was some 2.25 GW.



	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Rest	3,00	4,00	4,70	5,00	4,60	4,40	5,60	6,35	9,75	9,40	18,70	20,50	23,42	32,62	55,50
USA	11,1	14,1	14,8	17,1	18,1	22,44	25,64	34,75	38,85	51	53,7	60,8	74,97	100,3	120,6
Japan	12,8	14,2	16,8	19,9	18,8	16,7	16,5	16,4	21,2	35	49	80	128,6	171,2	251,1
Europe	6,7	7,9	10,2	13,4	16,4	16,55	21,7	20,1	18,8	30,4	33,5	40	60,66	86,38	135,1

Figure 2-19: Development of world PV module production between 1988 and 2002 in MW_p [JRC 2003] based on PV News

Recent data for 2003 show the following regional production volume: Europe 140.9 MW, Japan 247.2 MW, USA 96.3 MW, Rest of world 85.7 MW. This shifts the cumulative produced volume slightly above 3 GW.

Approximately 2% of annual PV production (i.e. 9.2 MW_p in 2001) is used for indoor applications, such as calculators, watches, lights and so forth [Maycock 2002].

The PV industry is growing at a high pace. During the last ten years, market growth rates were between 14% and as much as 43% annually. See Figure 2-20 for more details on the development of the market growth rate per annum.

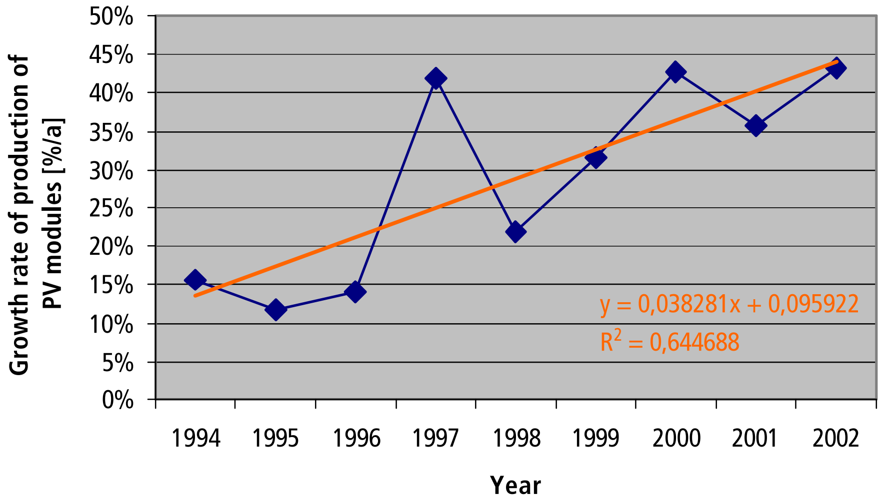


Figure 2-20: Historical growth rates of the annual PV production volume [JRC 2003]

Figure 2-21 extrapolates the historical market development for the near future (2010).

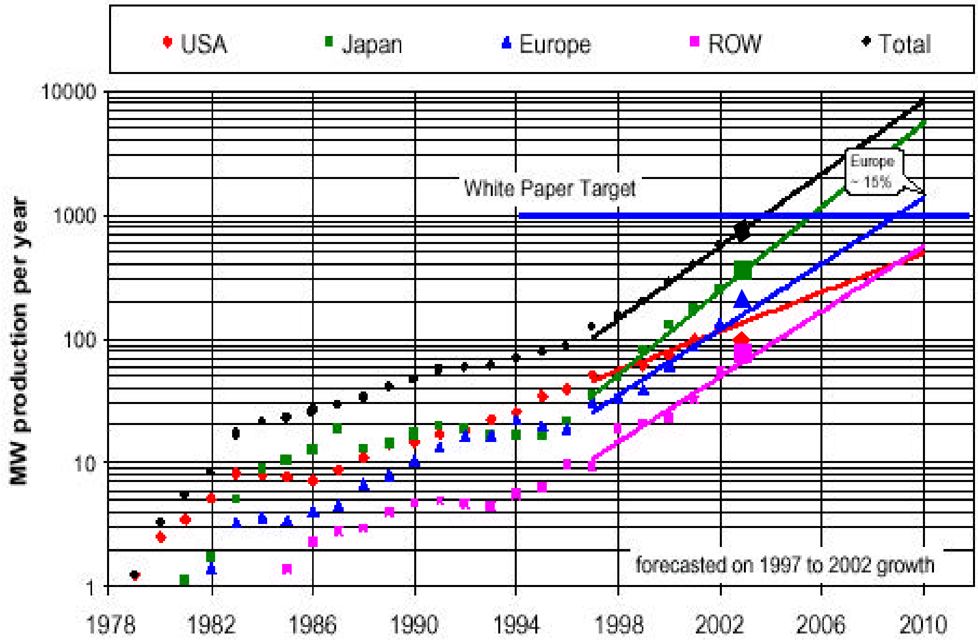


Figure 2-21: Near term increase of production capacities on the basis of historic growth rates between 1997 and 2002 [IEA 2003]

For the last two decades the solar cell market expanded with an average rate of about 20%. Largest production share was at companies in USA and Japan. However, over the last five years the market has changed dramatically. The growth rate doubled with an average growth of 37% per year for the last five years. Whereas the growth of US companies decelerated with an actual decline, all other parts of the world took part in that accelerated market expansion.

The following Figure 2-22 gives an overview regarding the historical learning curve on cost reductions of the past 20 years. With each doubling of the production experience prices reduced by about 20 percent.

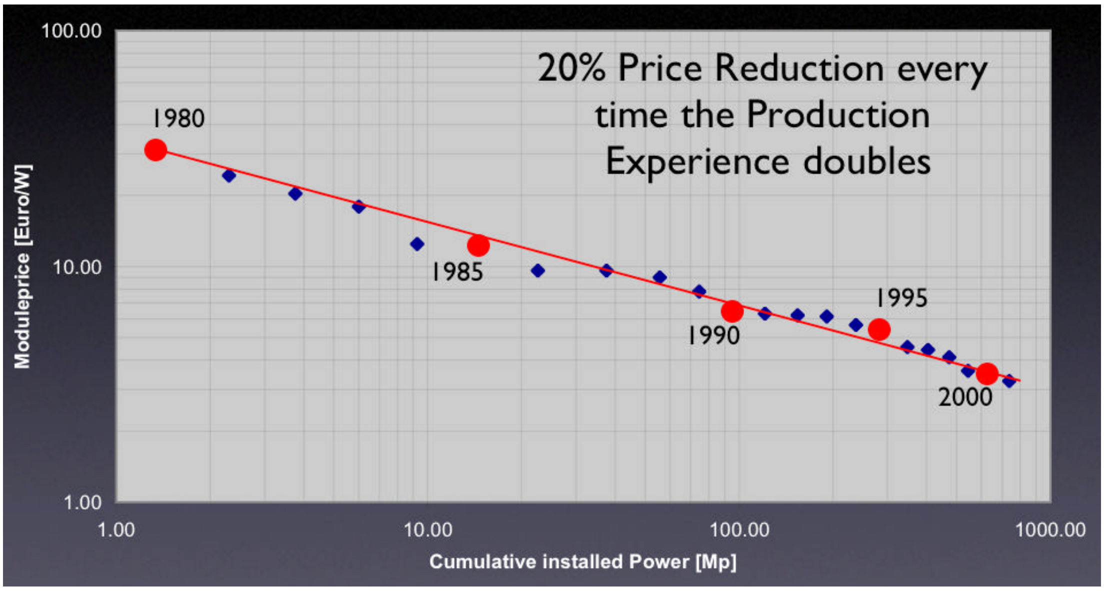


Figure 2-22: Price development of module prices over the last 20 years [TNC 2004]

b) Future market expectations

At present solar electricity production contributes with 0.025% to world electricity production of ~16,000 TWh. For many years it was conventional wisdom that PV will have a share of less than 1 percent on total electricity production, at least until 2020-2030. This figure was based on the extrapolation of a 15% growth rate over the next decades. Only very few consultants and companies realized that the market for solar electricity production could expand much faster as soon as some of its barriers are overcome. For instance, the Swiss based Sarasin Bank learned in 1999 from a comparison with the cellular phone market that at around 2002/2003 such a rapid rise of market growth could start.

Basing our knowledge on present PV average growth rates of 37% it would be likely, that the present (2004) share of 0.025% to world electricity production would shift to some

3% in 2020, even when assuming 2% annual increase of total world electricity production. This seems to be surprisingly low. Yet, here we deal with exponential growth functions. Up to the year 2020, we are at the very beginning of global market penetration. Assuming continuous growth rates for PV and electricity consumption beyond 2020, electricity market capture for PV power plants could already reach some 22% in 2027. The potential increase of PV power generation is depicted in Figure 2-23 assuming growth rates below those of the last couple of years (logarithmic scaling).

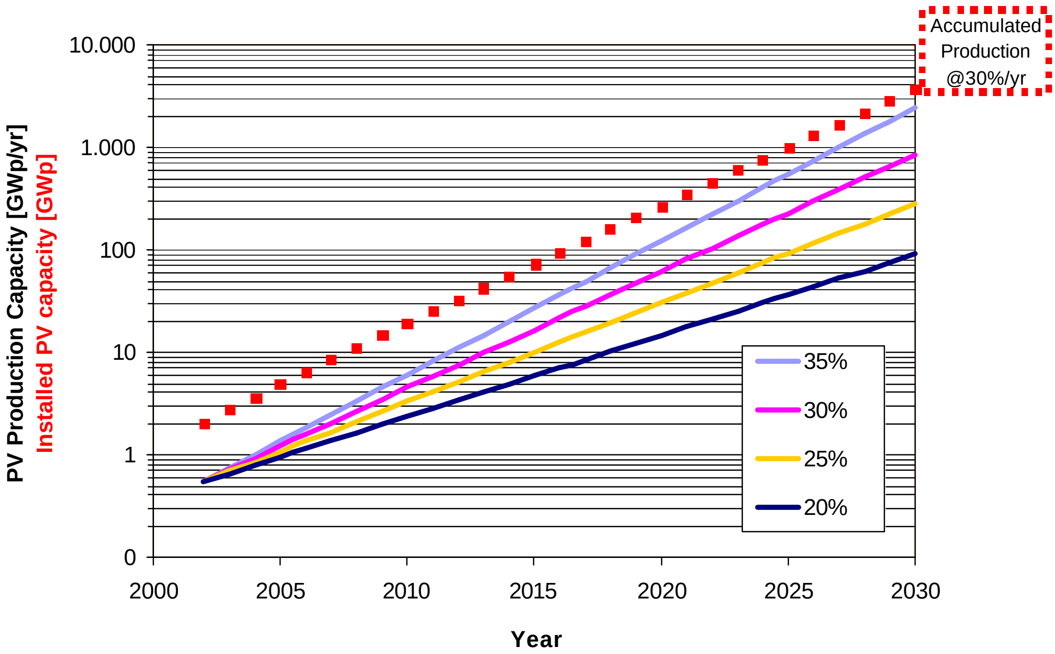


Figure 2-23: Growth of PV installed capacity and annual production capacity at various production capacity growth rates between 20%/yr and 35%/yr (LBST)

Whether the present growth rate of 37% continues for the next decades or reduces again, cannot be known. However, from the introduction of wind energy we do know, that such an average growth rate holds now for about two decades. This helped to bring the share of wind energy even today to about 0.4% of total world electricity supply, or to about 2 % in Europe where most of this growth was realized. And most of the world’s regions have not yet even started to use wind energy. Its “golden age” is still seen to come.

Comparing past and present developments it can be concluded that the PV market development is about one decade delayed with respect to wind energy at global scale.

There are arguments that the distribution of solar electricity could expand even faster once the price threshold of consumer electricity prices is met. PV doesn’t have a huge investment barrier. It doesn't need such a strong cooperation between society, regional politics, planning committees, credit banks, investors, environmental groups etc., to allow for its implementation.

Figure 2-24 sketches the future development as seen by the European Photovoltaics Industry Association (EPIA).

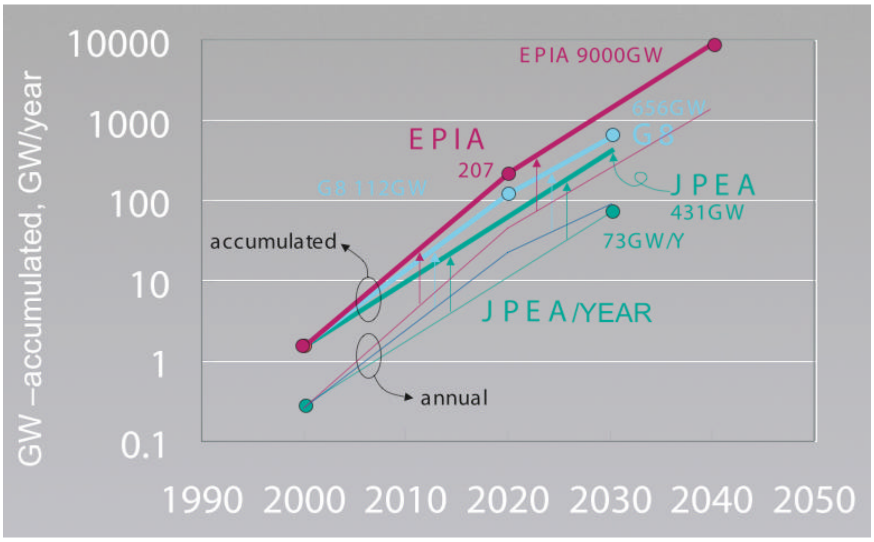


Figure 2-24 Estimated PV world market growth until 2040. The values show a worldwide accumulated PV power and annual additions as seen by the European Photovoltaics Industry Association (EPIA) [TNC 2004]

Combining a learning curve with market forecasts results in the conclusion that between 2006 and 2020 photovoltaic electricity production will become competitive with utility peak power supply, and one to two decades further with base load power supply. This development is sketched in Figure 2-25. However, it very likely might happen, that PV competitiveness starts already when the full electricity supply cost target to consumers is met.

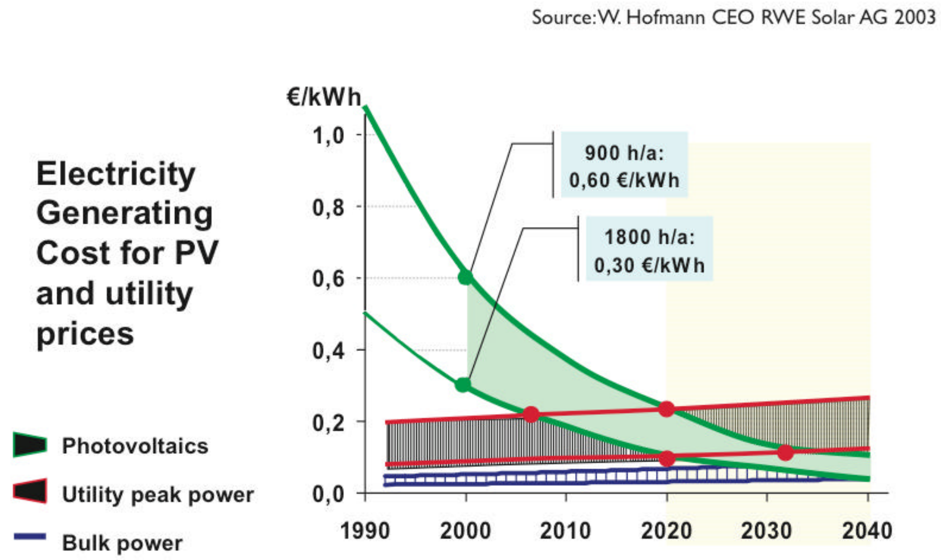


Figure 2-25 : PV competitiveness; break-even for PV power also depends on geographical issues such as radiation [TNC 2004]

c) Thin film prospects

More than 10 companies worldwide produce thin film silicon solar modules. Thin film silicon solar modules have a market share of less than 10% of the total annual production. Some four to five small companies are producing CIGS solar modules. Together they represent a market share below 1% of the total production. Nevertheless, the market share of thin film silicon is decreasing since 1998 due to the higher growth rate of polycrystalline solar modules. Furthermore, one of the more powerful supporter of silicon thin film technology – BP Solar – stopped its production in 2002.

The most prominent countries in the field of thin film research are US and Japan. Meanwhile, the research and development focus is more and more put on CIGS thin film technology, even in Europe. Special attention is given to micromorph solar cells which consist of an amorphous and a micro-crystalline silicon solar cells. Kaneka produces micromorph modules with a stable efficiency of 8%.

As reported by Photon International magazine, current thin film solar module price are roughly the same compared with c-Si solar module prices on a W_p basis. As only a thin layer of less than 3 µm is required for thin film solar cell fabrication, the resource effort is considerably lower compared to poly- and mono-crystalline silicon cells. Furthermore, the energy needed to fabricate thin film solar cells is 1/3 lower than energy needed to fabricate thick solar cells.

In future, thick solar cells will face the problem of silicon feed stock. Currently, the raw material is taken from microelectronic industries' silicon waste. Thus, the development of so-called 'solar-grade silicon' is critical for the further market growth of thick solar modules.

Cost reduction potentials with thin film technology are potentially high. The Music FM report (Multi-Megawatt Up-scaling of silicon and thin film solar cell and module manufacture) October 1996, with BP Solar, Phototronics, ZSW and Cythelia showed that it must be possible to reach 1 EUR/W_p with thin film solar modules.

d) Learning curve

At the first ESTEC workshop, it was jointly agreed to apply the same learning curve for system costs for both terrestrial thin film and poly/mono cell technology. Future costs of PV systems are derived in the following sub-chapters.

- Costs and learning curves for the latest installation

Based on past experience further cost reduction are easily estimated by extrapolating the historical learning pattern as exhibited in Figure 2-22.

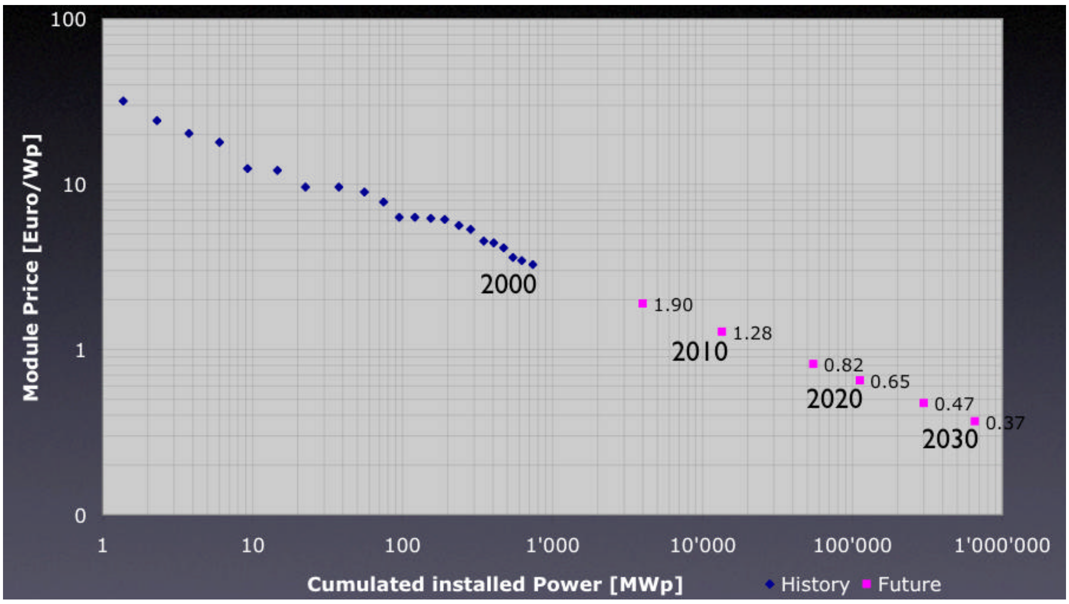


Figure 2-26 Extrapolation of module price model for 2010, 2020, 2030 according to the reduction model of Hoffmann (TNC)

At the first ESTEC workshop, it was jointly agreed to apply the following parameters for the learning curve for PV systems based on both terrestrial thin film and poly/mono crystalline technology:

- Learning curve start: 4,500 EUR/kW_p
- Learning curve factor: 20%

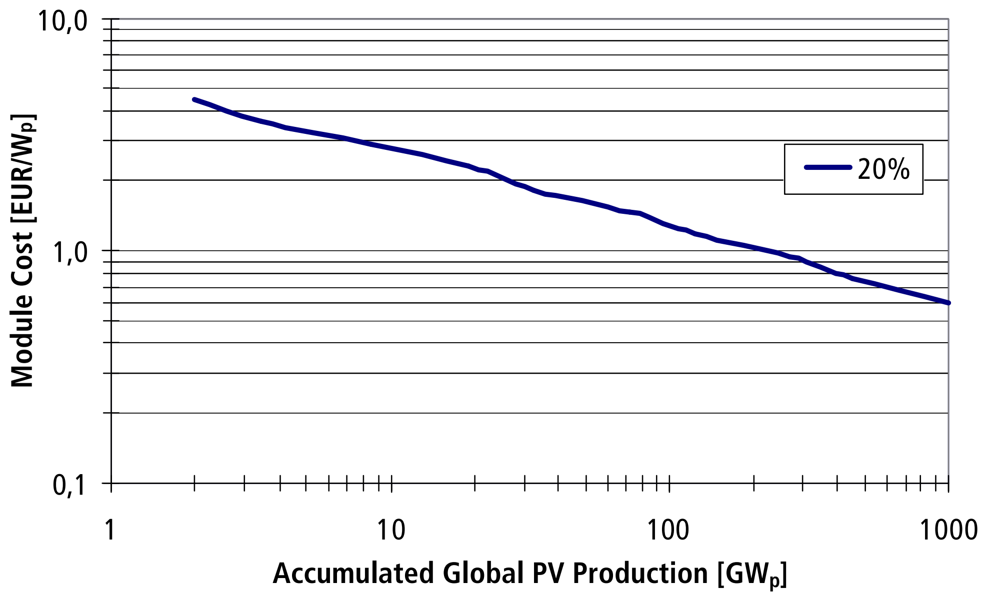


Figure 2-27: Development of module costs at an initial 2,000 MW_p (2002) installed capacity, initial module costs of 4.5 EUR/W_p and a learning rate of 20%

Some 2,250 MW_p [JRC 2003] of photovoltaic capacity has been installed by the end of 2002. The historical learning curve is best described by Equation 2-1:

$$C_2 = C_1 \cdot (1 - learning\ rate)^{\log_2\left(\frac{P_2}{P_1}\right)}$$

Equation 2-1: Learning curve equation to calculate the cost of nth unit

where

C_2 Cost in EUR per W_p at an installed capacity of P_2

C_1 Cost in EUR per W_p at an installed capacity of P_1 (starting point)

P_2 Cumulative installed capacity

E.g. a learning rate of 20% can be best described with a 20% cost reduction at each doubling of production volume.

The learning rate is different for the different components of the PV plant. The learning rate for the photovoltaic modules has been assumed to be 20%, and the learning rate for the DC/AC converter has been assumed to be 5%. The investment for the balance of plant (e.g. cables, installation etc.) will decrease only slightly. According to the data provided by TNC the learning rate is only about 3%.

The reason for the different learning rates of PV modules and BOP components is that the cost of PV modules is mostly technology-based. In contrast, BOS components are established technologies with long track records and a large number of units already in operation. The cost of BOS components are mostly driven by the cost of the primary material such as copper, glass, polymers etc. Future cost reductions for PV systems will thus benefit the still untapped cost reduction potentials of PV cell and module production.

Table 2-3 shows the specific investment after the installation of n^{th} MW_p depending on the installed capacity.

Installed capacity [MW_p]	PV module [EUR/W_p]	DC/AC converter [EUR/W_p]	BOP [EUR/W_p]	Total [EUR/W_p]
2,225	2.76	0.52	1.30	4.58
5,000	2.13	0.49	3.87	6.48
10,000	1.70	0.46	1.22	3.38
50,000	1.01	0.41	1.13	2.56
200,000	0.65	0.37	1.07	2.08
656,000	0.44	0.34	1.01	1.79

Table 2-3: Investment figures in EUR per W_p after the installation of n^{th} MW_p as intermediate result

- Cost and learning curve in average for all installations

For the calculation of the levelized electricity costs (LEC) for the different scenarios the investment both for the first and the last plants have to be taken into account. The calculation of the average investment over the scenario is carried out via integration of the learning curve and subsequently division of the integral by the total installed capacity.

$$C_2 = \frac{C_1}{P_2} \cdot \int_{P_1}^{P_2} (1 - learning\ rate)^{\log_2\left(\frac{P}{P_1}\right)} dP$$

$$C_{average} = C_1 \cdot \frac{P_1}{\frac{\ln(1 - learning\ rate)}{\ln(2)} + 1} \cdot \left(\frac{P_2}{P_1}\right)^{\left(\frac{\ln(1 - learning rate)}{\ln(2)} + 1\right)} \cdot \frac{1}{P_2} - 1$$

Equation 2-2: Learning curve equation to calculate the average costs of a given number of units

where

$C_{average}$ Average costs per W_p

This results in the following specific cost figures which had to be paid in average to cover the installed capacity as given in the table. Note that Table 2-4 gives the same disaggregation as Table 2-3. But in contrast to Table 2-3, these figures are average figures over the period of cost degression.

Installed capacity [MW_p]	PV module [EUR/W_p]	DC/AC converter [EUR/W_p]	BOP [EUR/W_p]	Total [EUR/W_p]
2,225	4.07	0.56	1.36	5.99
5,000	3.14	0.52	1.31	4.97
10,000	2.51	0.50	1.27	4.28
50,000	1.49	0.44	1.19	3.12
200,000	0.96	0.40	1.12	2.47
656,000	0.65	0.37	1.06	2.08

Table 2-4: Average investment figures derived from cumulative investment

Finally, the total cost degression is shown in Figure 2-28 with a comparison of the difference between specific installation cost of last installation and specific installation cost in average from first to last installation. As expected, the specific costs of the last installation are cheaper than average cost, but, the more the market expands, the more this difference diminishes.

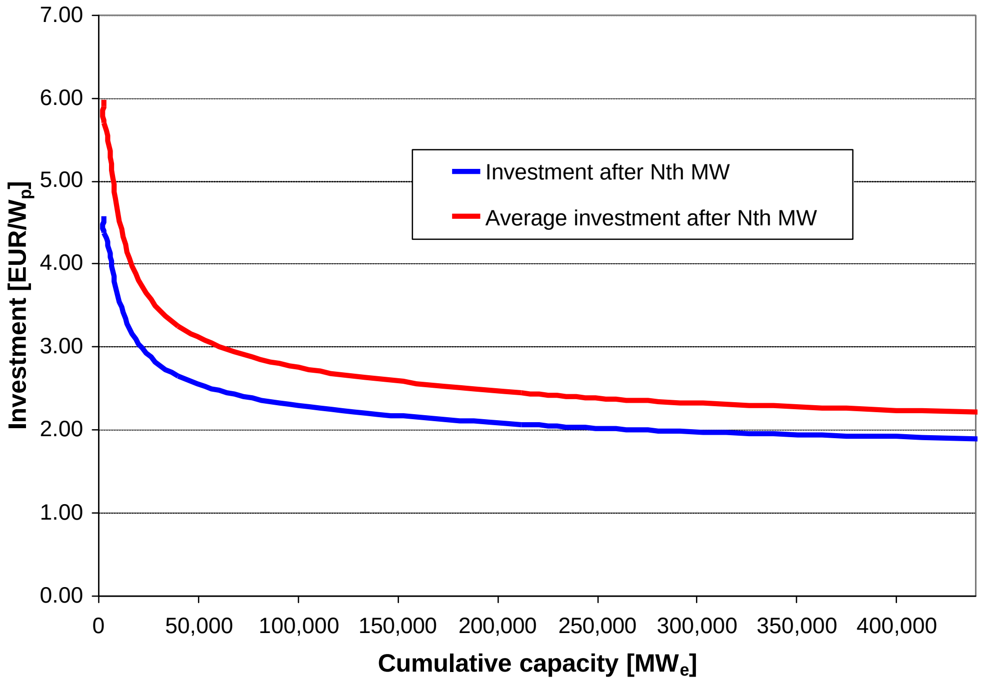


Figure 2-28: Specific investment for PV plants depending on the cumulative installed capacity

The resulting levellized electricity costs are compiled in Table 2-5. The results are based on the following assumptions:

- Power Supply: 5 kW_p
- Required land area: 0 m²/plant (distributed on rooftops, sound barriers etc.)
- Average equivalent full load period (EU sunbelt): 1,335 h/yr
- System efficiency: 14%
- Lifetime: 30 yrs
- Interest rate: 6%
- O&M: 1.5% of investment cost per year

Installed capacity [MW_p]	LEC of n[th] system [EUR/kWh_e]	Average LEC [EUR/kWh_e]
2,225	0.300	0.393
5,000	0.254	0.326
10,000	0.222	0.281
50,000	0.168	0.205
200,000	0.137	0.162
656,000	0.118	0.136

Table 2-5: Reference PV system: Levellized electricity cost depending on the cumulated production of PV systems

2.2 Solar thermal (SOT) power plants

Solar thermal power plants were investigated first in the United States of America during the years following the oil price shocks of the 70ies. Around 1985 oil prices collapsed again and fears of diminishing oil supplies disappeared. The favorable research environment disappeared as well: Tax credits and research funding were reduced hindering further fast developments and introduction of the technologies. Nevertheless, the experience gained at that time set the basis for today's proposals and estimated learning curves. Enough knowledge had been accumulated to make sound extrapolations on future developments. In contrast to these early days, today we know the technologies, their performances and potentials. We just have to start using them. Of course surprises will still happen, but instead of relying on future breakthroughs, further developments and cost reductions are straightforward and calculable with reasonable assumptions.

2.2.1 Technologies

Solar thermal power plants (SOT) use direct solar irradiation which is converted into thermal energy. A heat transfer medium (thermal oil, steam, air or melted salt) transports the thermal energy to the power block with a conventional power cycle, such as a steam or gas turbine, or a Stirling engine for electricity production.

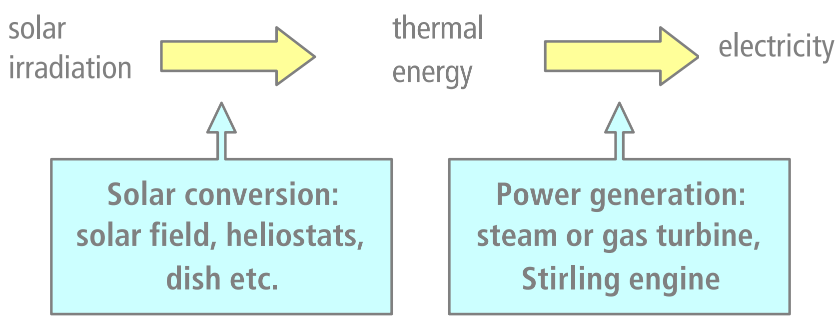


Figure 2-29: Solar thermal conversion technologies

SOT plants must be sited in regions with high direct solar irradiation within 20 degree latitude north or south of the equator. Outside this band the increasing fraction of diffuse radiation cannot be concentrated to a central (or linear) receiver resulting in reduced energy conversion efficiency.

For European power supply scenarios SOT plants should be favored installed in North Africa or in southern regions of Europe (European sunbelt, such as Spain, Portugal, Italy, Greece, Turkey).

In the following subchapters four different technologies of solar thermal power plants are considered and evaluated for terrestrial concepts before the most promising technology is selected in chapter 2.2.2 for further scenario evaluations:

- Parabolic trough
- Central receiver
- Parabolic dish
- Solar power tower (solar chimney power plant)

a) Parabolic trough

A parabolic trough consists of one dimensional concentrating modules typically trough-shaped glass mirrors or segmented mirrors. The mirrors concentrate the direct solar irradiation onto the absorber tube centered in the focus of each parabolic shaped module. The troughs track the sun light from East to West by rotation along their symmetry axis for gaining highest solar irradiation.

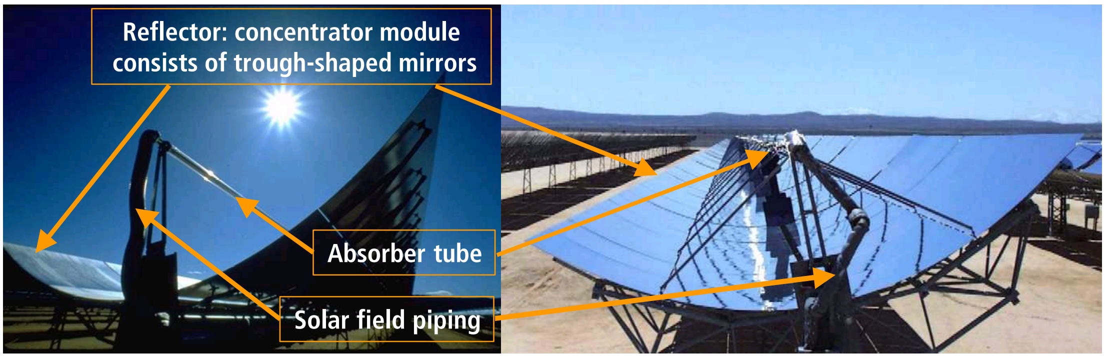


Figure 2-30: Parabolic trough: absorber/concentrator module [KJC 2003]

A thermal transfer fluid, such as synthetic thermal oil circulates through the absorber pipe and transports the heat through a series of heat exchangers. The heat is used to produce hot steam which is supplied to the power block for electricity production via a hot air turbine. The transfer fluid is heated up to around 400°C. New concepts use the principle of direct steam generation without the need of an additional thermal oil and heat exchanger. Such systems are under development for increased operation temperature up to 500°C.

Concentrator modules are installed in long parallel rows as seen in Figure 2-31 which shows SEGS plants in California.

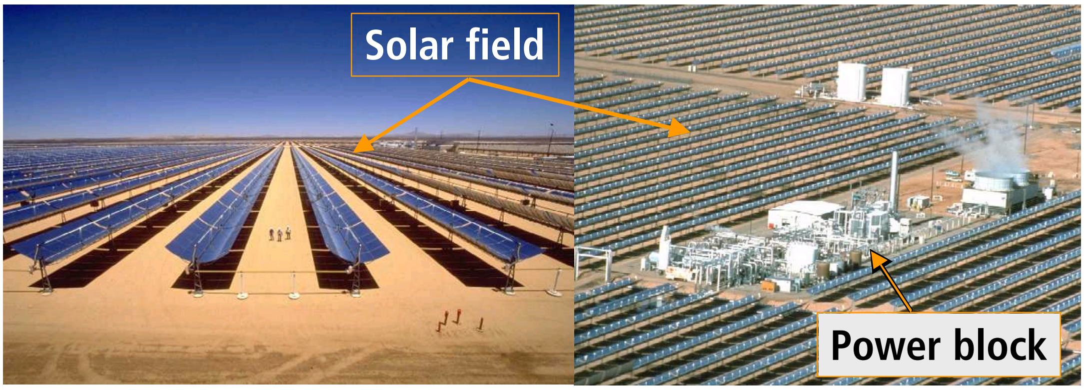


Figure 2-31: Parabolic trough plants consists of solar field with parallel rows of concentrator modules and a power block [KJC 2003]

Commercial parabolic trough plants have been build in modules of between 14 MW to 80 MW_e by so far. Today the upper size for commercial plants is typically at around 400 MW_e. Early solar power plants have been build since 1980s, like the SSPS plant in Almeria, Spain (1981) with a power capacity of 0.5 MW_e. The largest solar thermal power plant installations are the SEGS (Solar Energy Generation Systems) plants. Between 1984 and 1991 nine parabolic trough plants with a total capacity of 354 MW_e have been constructed in the California Mojave desert. Power plant sizes range from 14 MW_e to 80 MW_e. To increase total operating hours of the generator, some of these plants have integrated gas-fired back-up burners, see Figure 2-32. These co-fire the generator during phases of missing solar irradiation.

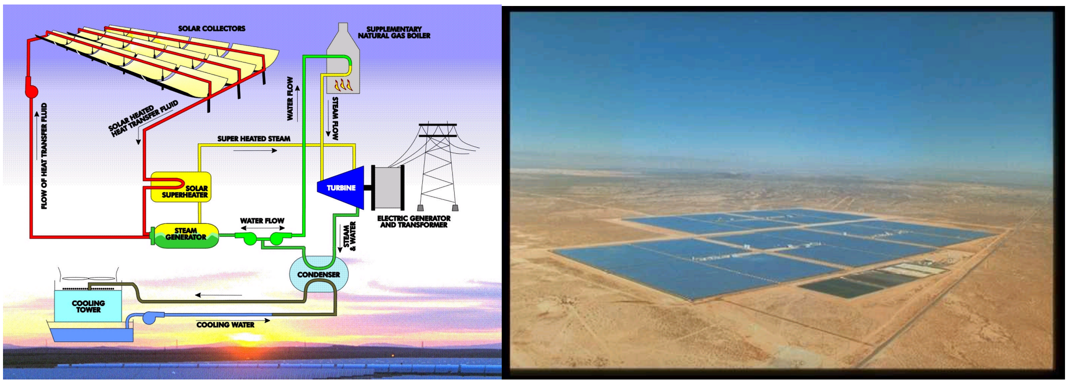


Figure 2-32: SEGS plants in California [KJC 2003]

According to geometrical considerations, one dimensional concentrators increase the solar flux density in the focus of the receiver to a maximum of about 200 times standard conditions. Realistic concentration factors are below that figure and are due to the quality of the mirror surfaces .

b) Central receiver

Two dimensional concentrators reach concentration ratios of up to 200 x 200 = 40.000 with ideal mirror surface. Therefore central receivers with two dimensional concentration reach much higher temperatures, which translate into higher Carnot efficiency of the electricity generation. On the other hand, higher operating temperatures result in higher requirements on materials, larger thermal losses and higher material cost. Detailed experience and systems analysis has to figure out which system yields best operating performance at lowest specific cost.

A central receiver solar power plant consists of several heliostats typically planar mirrors, a central receiver tower and a power block for electricity generation. The mirrors (heliostats) concentrate the direct solar irradiation onto the receiver on top of the in the middle of the heliostats field centered tower. Each heliostat is 2-axial mounted for optimized solar irradiation tracking.

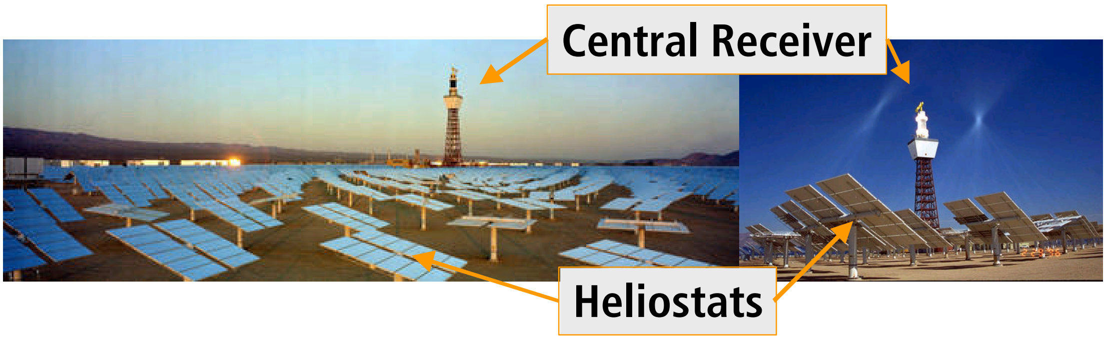


Figure 2-33: Central receiver: Heliostats (mirrors) and central receiver tower [NREL 2003]

A thermal transfer fluid, such as water/steam, molten salts, liquid sodium or air flows through the central receiver at the top of the tower. The heat transfer medium absorbs the thermal energy from highly concentrated solar irradiation and transports the thermal energy to the power block for electricity production via superheated steam. Operating temperatures are proven for 565°C. New concepts show a potential up to ~1,100°C.

Concentrator modules are installed in circular around the central receiver tower, as shown in Figure 2-34.

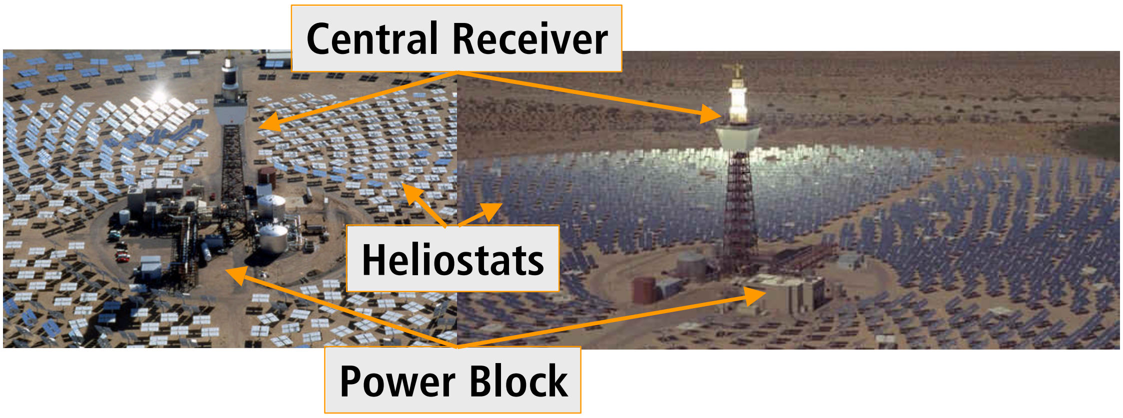


Figure 2-34: A central receiver plant consists of heliostat field, central receiver tower and power block. The pictures show the "Solar Two" plant in California [NREL 2003]

Central receiver solar tower plants have been build up to 15 MW_e by so far, see Figure 2-35. Today the upper size for commercial plants is typically seen between 200 to 400 MW_e. The size is limited by geometric factors and the deviation of the mirror surface from ideal conditions. These factors determine the minimal diameter of the focus of the receiver.

Early solar power plants have been build since 1980s, see listed examples below:

Date	Size [MW_e]	Name (heat transfer medium); Location
1981	1	Adrano(Water-Steam); Sicily, Italy
1981	0.5	SSPS (Sodium); Almeria, Spain
1981	0.5	Sunshine (Water-Steam); Nio, Japan
1982	10	Solar One (Water-Steam); California, USA
1982	2.5	Themis (Molten Salt); Targasonne, France
1983	1	CESA-1 (Water-Steam); Almeria, Spain
1984	0.75	MSEE (Molten Salt); Albuquerque, USA
1985	5	C3C-5 (Water-Steam); Crimea, Russia

Figure 2-35: Technology experiences for over 20 years: overview of selected central receiver solar plant installations [Greenpeace 2003]

Between 1997 and 1999 the Solar Two plant was successfully operated in California. The CR plant based on the Solar One technology. The 10 MW_e Solar Two plant was operated with an integrated molten salt storage system. Based on this concepts "Solar Tres" will be erected with a larger thermal storage capacity for 24 h operation in Spain. Its details are discussed under the "Solar Tres" project description in chapter 2.2.2.

c) Parabolic dish

A parabolic dish solar power plant usually consists of a parabolic dish-shaped reflector. Some dish concepts, however, use single individual small mirrors for as reflector. The reflector concentrates the solar irradiation onto the receiver located in the focal point of the dish. The thermal energy is converted by a Stirling engine or micro turbine into electricity which is located at the receiver above the reflector dish. Solar dish plants are 2-axial mounted for optimized solar irradiation tracking.

Different to central receivers, solar dishes are highly modular with unit size of between 5 – 50 kW_e, at maximum. Larger power requirements are to be met by adding the appropriate number of the individual modules. Therefore no cost reduction (or efficiency increase) can be expected due to large system units.

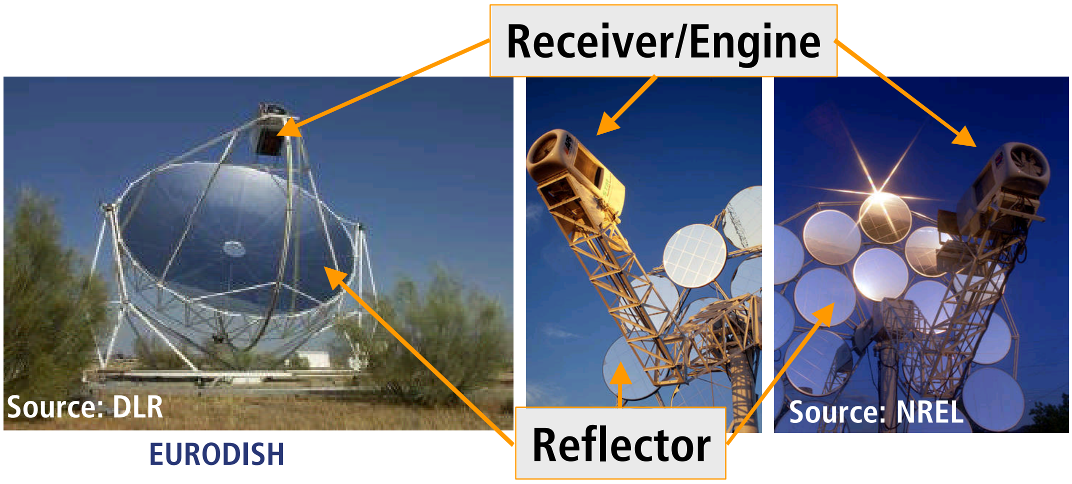


Figure 2-36: Solar Dish: left: parabolic dish with parabolic reflector and stirling engine, EURODISH, source: [DLR SOT]; middle and right: solar dish, Arizona with single reflector mirrors and receiver/engine [NREL 2003]

Parabolic or solar dish plants typically use helium as working fluid and operate at temperatures up to 750°C. These systems are suited for stand-alone applications or small off-grid power systems due to their high modularity and option for hybrid operation.

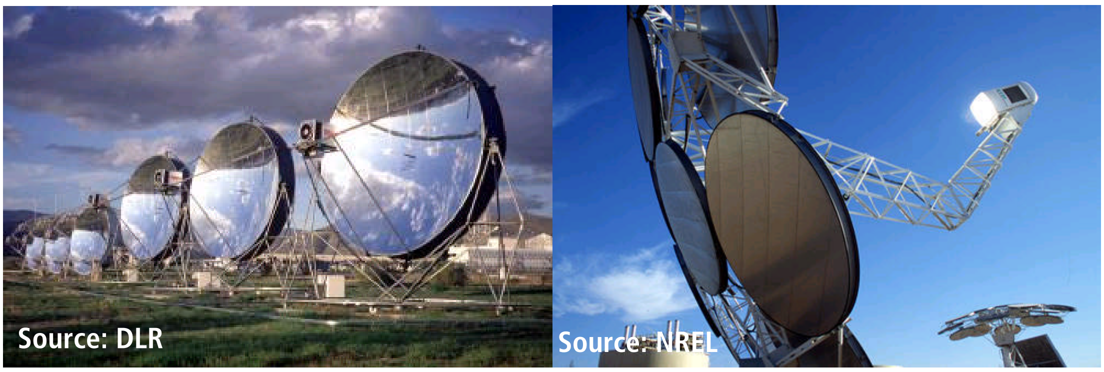


Figure 2-37: Solar Dish: left: parabolic dish installations, source: [DLR SOT]; right: solar dish plant in Arizona [NREL 2003].

First prototype systems have been built in the 1980s, such as the Vanguard-1 by Advanco Corp., USA (1984) or the MDA by McDonnell-Douglas, USA (1984), both with power capacities of 0.025 MW_e

d) Solar power tower (solar chimney power plant)

Completely different to the above described technologies is the solar chimney concept. Instead of concentrating direct solar irradiation, low temperature heat is produced via the "greenhouse effect" under huge areas of conventional flow glass. The heat moves upward to the central chimney, producing upwinds with high velocity.

The electricity is generated by wind turbines installed inside the lower part of the chimney tower. In the greenhouse of the plant which consists of a large surface of circular installed collectors air is heated and flows into the chimney tower by passing the wind turbines. For the collector area low quality glass can be used for the greenhouse segments which lower strongly the investment costs compared with other SOT concepts which need expensive mirrors for solar irradiation concentration onto a absorber/receiver. The simple concept of guying the concrete tower enables low cost tower construction.

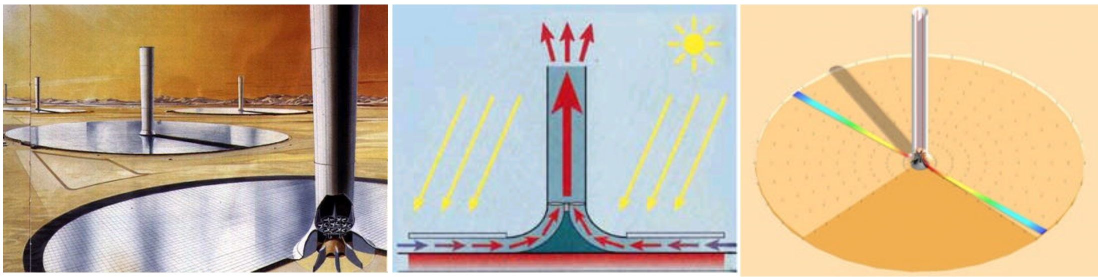


Figure 2-38: Solar power tower consists of large, circular, low cost collector area (greenhouse), a chimney tower and wind turbines; left: [ArchInForm]; middle: [Solar Millennium]; right: [SBP 2003]

The potential power output for commercial plants is between 200 and 400 MW_e. Figure 2-39 shows the model of a 200 MW_e which is planned for Australia.

Figure 2-39: Concepts for a 200 MW_e power plant in Australia [SBP 2003]

Typical tower dimensions for power supply of 200 – 400 MW_e are a chimney with ~ 1,500 m height and inner diameter of 160 m. At the bottom 8 turbines are installed with 25-50 MW, each. The total glas covered collector area is around 38 km² with an inner dry area of 13 km² (peak power) and an outer "greenhouse" area with 25 km² (base load).

Plants are designed for low cost electricity generation with high capacity factors up to 85% equivalent to 7445 full load hours per year. Humus soil and water storage (pond) act as thermal storage for up to 72 h full power supply. [SBP]

In 1986 a first prototype plant was erected in Manzanares, Spain. The plant had a power capacity of 50 kW_e, a tower height of ~ 200 meters and basement diameter of ~ 122 m, see Figure 2-40.

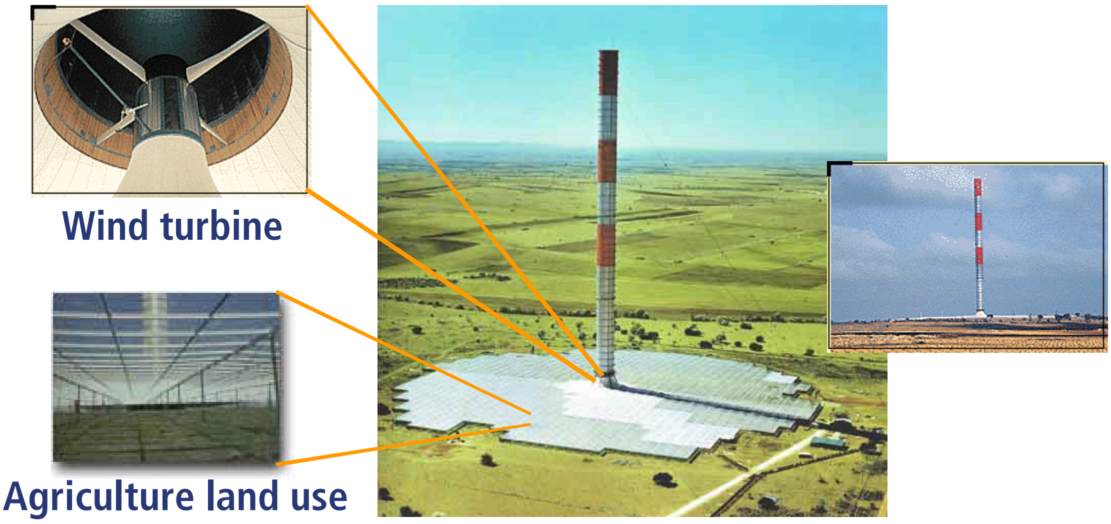


Figure 2-40: 50 kW_e prototype plant in Manzanares, Spain [Solar Millennium]

Until today too less experience and data from operating prototypes exist. Therefore this technology is not further considered for terrestrial concepts in this study. But nevertheless, theoretical calculations exhibit its high potential for future investigations.

2.2.2 Selected Technologies

For the further investigation and discussion of SOT concepts parabolic trough and central receiver plants are favored, and are chosen as reference technologies in this chapter. Both technologies are proven, and sufficient data from more than twenty years practical experience are collected and available. Also recent published studies, e.g. [S&L 2003], [Greenpeace 2003], [DOE 2002], as well as several publications from the National Renewable Energy Laboratory [NREL 2003], the German Aerospace Center (DLR) or publications such as [BMU 2002], [Nogueira 2002] are focused on parabolic trough and central receiver technologies.

For WP1 "base load scenarios" SOT plants with high capacity factors are identified as the technology of choice to achieve the target of uninterrupted electricity supply for 8,760 full load hours per year. Therefore SOT plants with integrated thermal storage are favored. Such concepts with additional thermal storage are already designed and planned for projects with parabolic troughs and central receivers.

Parabolic or solar dish plants and solar chimney towers are not selected and not investigated further for the scenario evaluations in the following chapters. For both technologies too poor experience and validated data are available. For parabolic dishes the reliability still must be improved and further progress is needed to achieve projected cost targets for mass production. Also for solar chimney towers validated data are still missing. As already described, up to date, only one prototype demonstrator plant with 50 kW_e capacity was operated during the early 90ies.

For the base load scenarios with high power demand (up to 500 GW_e) systems with large power capacity per module such as CR or parabolic trough are favored. Both technologies, central receiver and parabolic trough, are already close to commercialization. Figure 2-41 shows the locations for current projects of new advanced parabolic trough and central receiver plants in Spain under planning or construction. These projects are described in the following.

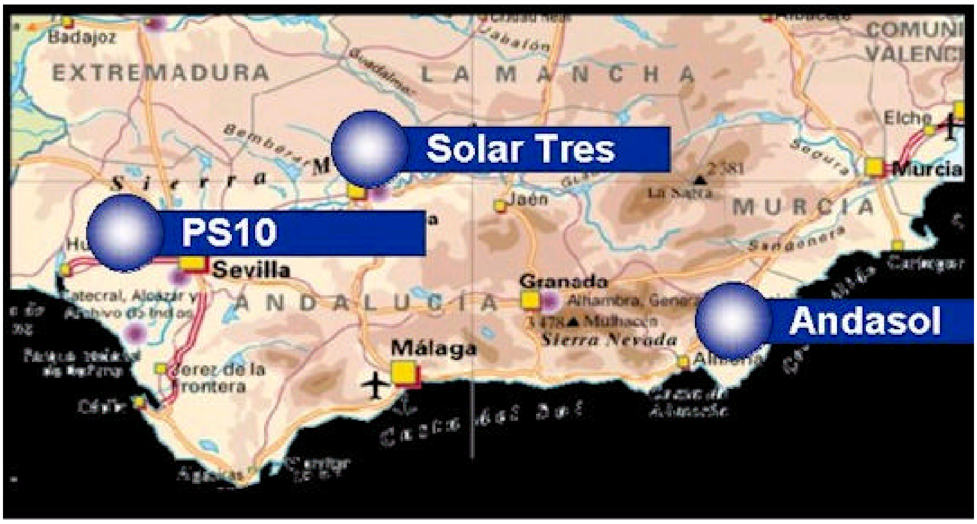


Figure 2-41: Map of current SOT demonstrations in Spain [Solarpaces 2003].

- PS10: Planta Solar 10 MW_e

The PS10 plant will be built according to present planning near Seville in Spain with financial support from the 4th and 5th European Framework program. The final plant will contain 981 heliostats, a 90 meter high tower, an integrated volumetric air receiver and a 33 MWh thermal storage. The system concept is sketched in Figure 2-42. Single components are already constructed. For example, the central receiver and a single heliostat are shown in Figure 2-43. Project parameters are summarized in Table 2-6.

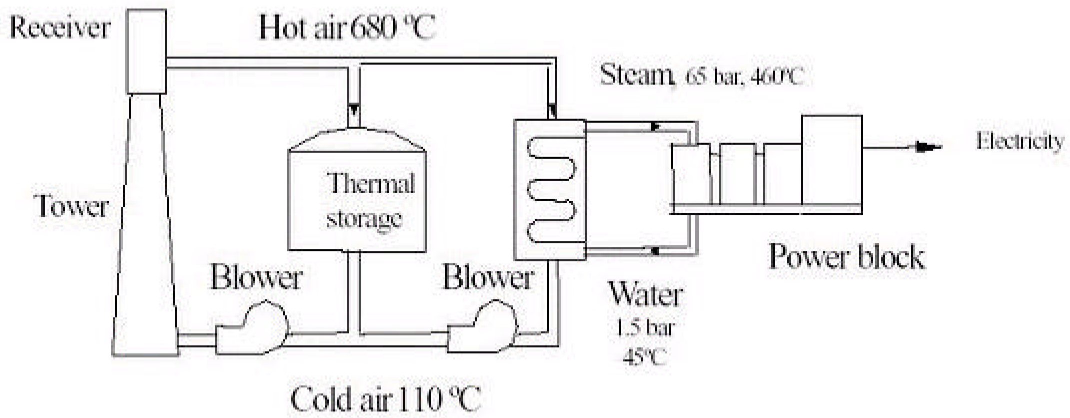


Figure 2-42: Process flow diagram of PS10 [Solarpaces 2003]

Figure 2-43: PS10 receiver and heliostat [Solarpaces 2003]

The PS10 plant should achieve a capacity factor of 22% with a pure solar operation mode. The installed cost target is below 2,800 $/kW.

Table 1. PS10 SOLAR PLANT DESIGN PARAMETERS		
Annual Irradiation [kWh/m²]		2063
Design Point Day		355 (noon)
Design Point Irradiance [W/m²] / Design Point Power [MWe]		850 / 10
Solar Multiple		1.15
Tower Height [m]		90
Heliostats Number/ Heliostat Reflective Surface [m²]		981 / 91
Heliostat Annual Average Reflectivity/Beam quality (mrad)		0.90 / 2.8
Receiver Shape [m]		Half cylinder
Receiver diameter [m] / Receiver Height [m]		10.5 / 10.5
	DESIGN POINT	ANNUAL BALANCE
Power/Energy onto Reflective Surface	75.88 MW	183.50 GWh
Heliostat Field Optic Efficiency	0.729	0.647
Gross Power/Energy onto Receiver	55.27 MW	118.72 GWh
Receiver and Air Circuit Efficiency	0.740	0.614
Power/Energy to Working Fluid	40.92 MW	72.90 GWh
Power/Energy to Storage	5.34 MW	
Power/Energy to Turbine	35.58 MW	72.90 GWh
Thermal->Electric Efficiency	0.309	0.303
Gross Electric Power/Energy	11.00 MW	22.09 GWh
Net Electric Power/Energy	10.00 MW	19.20 GWh

Table 2-6: PS10 solar plant design parameters [Solarpaces 2003]

- Solar Tres: 15 MW_e

Under the 5th Framework Program the European Union finances the development and construction of the Solar Tres power plant in Spain. This 15 MW_e power plant is based on the experience gained from 10 MW_e models of the Californian Solar One (1982-1988) and Solar Two (1996-1999) and will generate 24 hours base load, as described in Figure 2-44 and Figure 2-48. The "Solar Two" concept is sketched in Figure 2-47.

The central receiver plant concept of Solar Tres includes an integrated 16 hours thermal storage concept (588 MW_{th}). The electricity power generation capacity is designed for 15 MW_e electrical output. The system will be located near Cordoba, Spain. With the additional molten-nitrate salt thermal storage the plant should supply 24 hour a day full electricity output. The capacity factor of the plant is 20-22%. The operation temperature between 290-565°C.

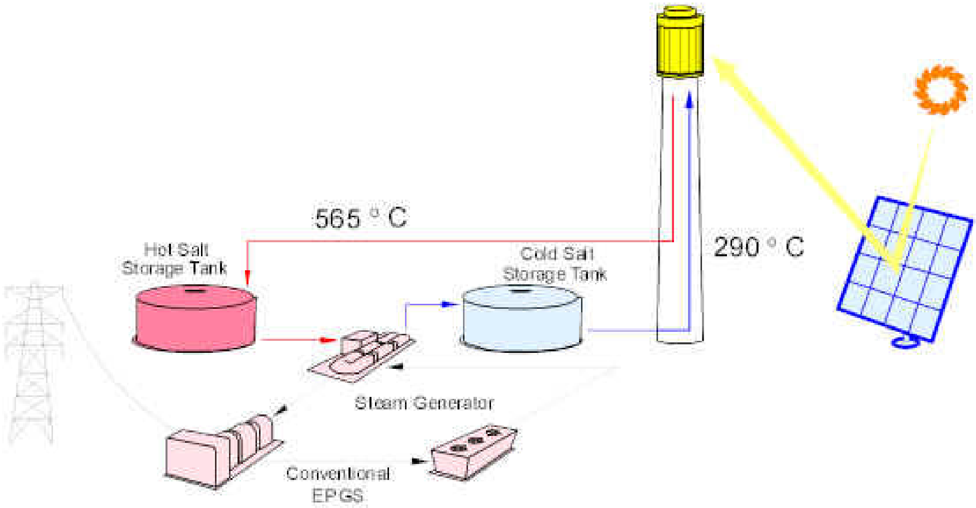


Figure 2-44: Solar Tres: concepts scheme [Solarpaces 2003]

- AndaSol: 2*50 MWe

In the AndaSol projects two 50 MW_e parabolic trough plants are planned with integrated thermal storage for nine hours. The parabolic trough field of about 540,000 m² consists of so called EuroTrough collectors (Figure 2-16). Projected full load hours are ~3,630 h/yr.

Figure 2-45: AndaSol: EuroTrough collectors [DLR 2003]

The total project costs amount to ~200 million Euro. The expected lifetime is around 25 years.

- Thermal storage

For terrestrial base solar power generation in this study SOT concepts with integrated thermal storage are selected. Figure 2-46 shows that specific electricity costs of SOT plants can be lowered with 9 – 16 hours thermal storage concepts. The storage concept helps to increase the operating hours of the steam and electricity generators, thus decreasing their specific cost. At a certain storage size this specific cost decrease overcompensates for the additional storage cost.

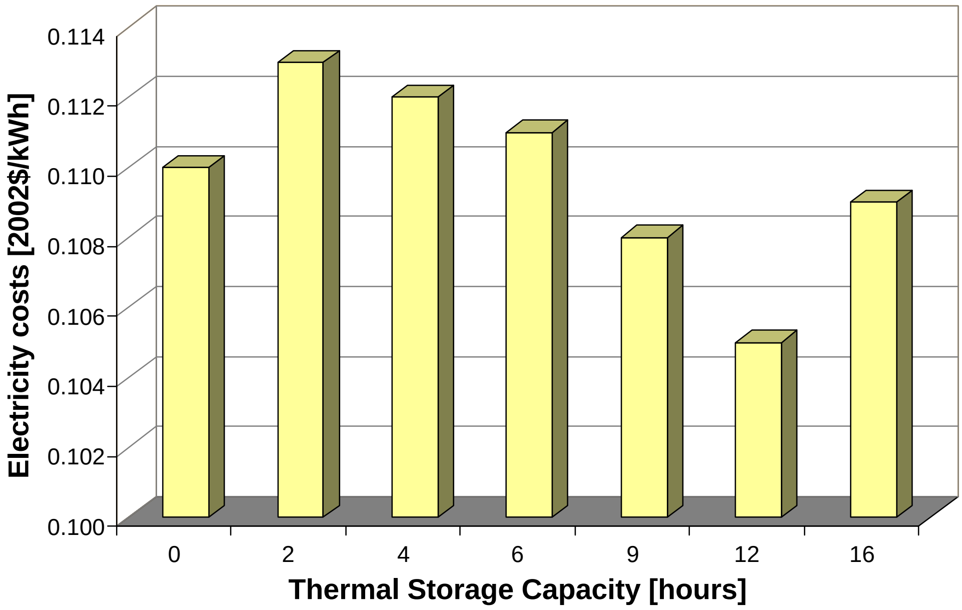


Figure 2-46: Comparison of electricity costs of a 50 MW$_e$ SOT (parabolic trough) plant with different thermal storage capacities [NREL/Kearney]

The diagram above shows that small amounts of thermal storage capacities up to six hours of full load operation increase the electricity costs of the SOT plant, while storage capacities between 6 and 16 hours lower the electricity costs.

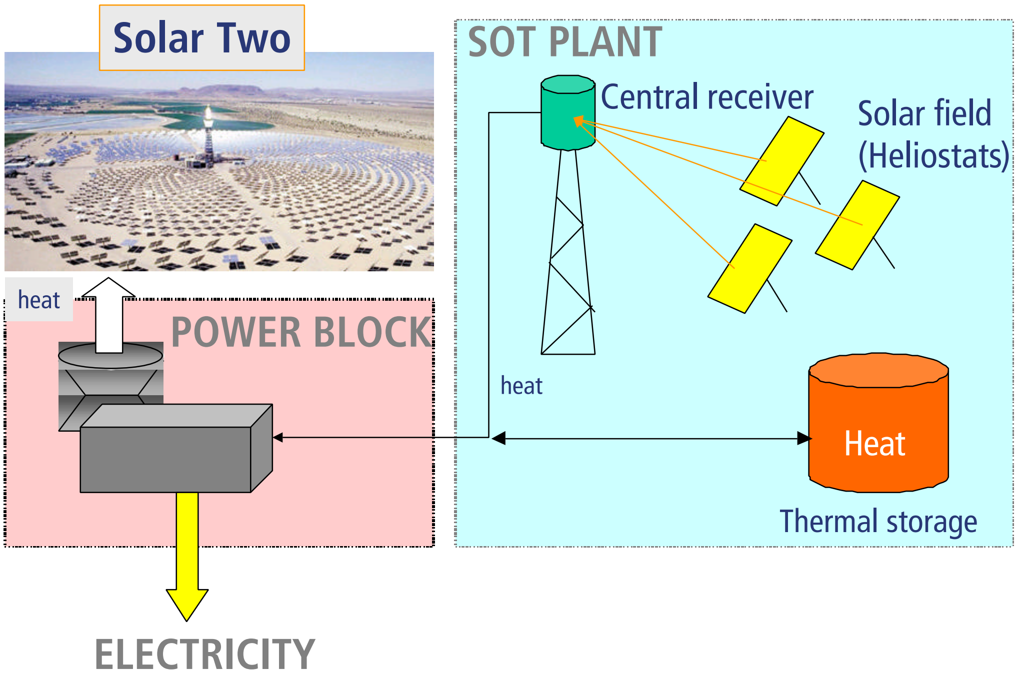


Figure 2-47: Scheme of central receiver plant with thermal storage and picture of Solar Two, a 10 MW_e prototype plant with thermal storage [NREL 2003].

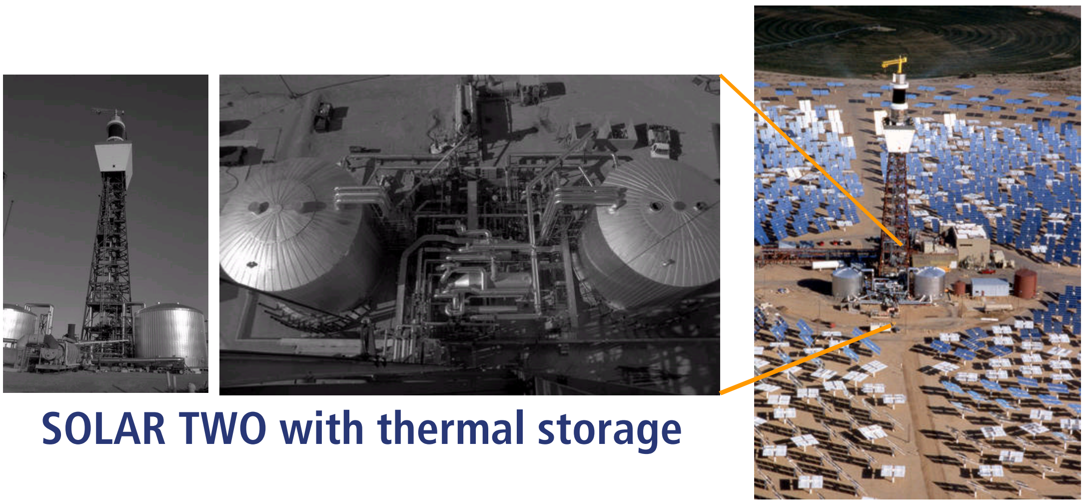


Figure 2-48: Experiences with thermal storage concept: Solar TWO with two thermal storage tanks (tanks for thermal storage; cold: > 290°C and hot: ~ 565°C) [NREL 2003]

For terrestrial concepts SOT plants with thermal storage between 9 to 16 hours are favored due to lowest electricity costs (see Figure 2-46). A detailed investigation shows that the optimal storage capacity is between 12-13 hours. Figure 2-49 shows that solar thermal power plants increase their solar capacity factor with an increase of the thermal storage size.

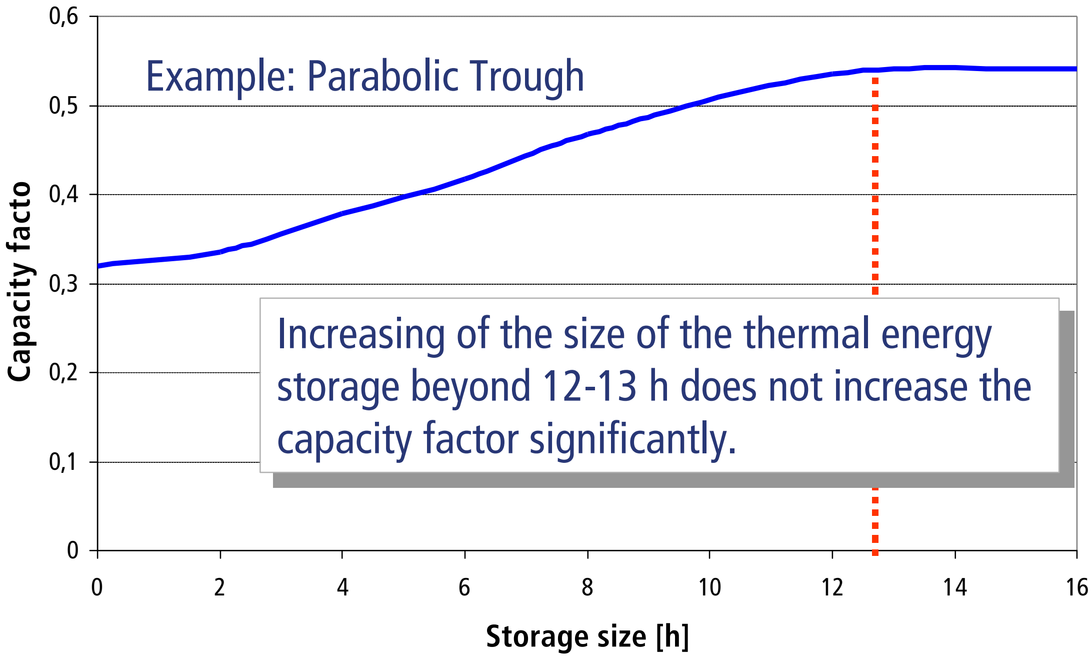


Figure 2-49: Thermal storage optimum: 12 to 13 hour capacity [S&L 2003]

The results of the work of [NREL/Kearney] and [S&L 2003] show that levelized electricity costs (LEC) for SOT plants are lowest for SOT plants with 12 to 13 hours storage capacities. As seen above, larger thermal storage tanks, e.g. 16 hours do not result in an increased capacity factor.

In a study prepared by [S&L 2003] for the Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL), USA, advanced parabolic trough and central receiver technologies are evaluated with cost and performance forecasts for 2020. In that study Sargent & Lundy (S&L) compares and discusses its results and assumptions with results of a comparable work done by the National Laboratory SunLab. Further cost estimates and extrapolations for this study are based on the results derived by the Sunlab study. In addition, S&L data are used to estimate the range of uncertainty.

Table 2-7 and Table 2-8 summarize the assumptions and predictions for the two favored and investigated SOT technologies with integrated optimized thermal storage. LEC are calculated by LBST without taxes and tax credits which were assumed and included in the original data from [S&L 2003].

	SunLab 2010	S&L 2010	SunLab 2020	S&L 2020	
Investment	2,876	3,562	2,221	3,220	US$/kW$_e$
Electricity output	150	150	400	400	MW
Investment	431,400,000	534,300,000	888,400,000	1,288,000,000	US$
Share equity	0.2	0.2	0.2	0.2	
Share dept	0.8	0.8	0.8	0.8	
IRR	11.5%	11.5%	11.5%	11.5%	
Interest rate dept	6.0%	6.0%	6.0%	6.0%	
Useful lifetime	30	30	30	30	yr
Debt term	20	20	20	20	yr
Capital costs	911,262,392	1,128,621,919	1,876,600,624	2,720,690,683	US$/(30 yr)
Equivalent full load period	4,906	4,906	4,993	4,993	h/a
Electricity generation	22,075,200,000	22,075,200,000	59,918,400,000	59,918,400,000	kWh/(30 yr)
Insurance	0.5%	0.5%	0.5%	0.5%	of investment/yr
Insurance	64,710,000	80,145,000	133,260,000	193,200,000	US$/(30 yr)
O&M	0.0135	0.0180	0.0097	0.0139	US$/kWh$_e$
LEC	0.058	0.073	0.043	0.063	US$/kWh$_e$

Table 2-7: Technical assumptions and cost predictions for parabolic trough plants with 12 h thermal storage capacity; LEC without taxes and tax credits (LBST derived from [S&L 2003])

	SunLab 2008	S&L 2010	SunLab 2018	S&L 2020	
Investment	3,103	4,608	2,272	3,139	US$/kW$_e$
Electricity output	100	100	220	220	MW
Investment	310,300,000	460,800,000	499,840,000	690,580,000	US$
Share equity	0.2	0.2	0.2	0.2	
Share dept	0.8	0.8	0.8	0.8	
IRR	11.5%	11.5%	11.5%	11.5%	
Interest rate dept	6.0%	6.0%	6.0%	6.0%	
Useful lifetime	30	30	30	30	yr
Debt term	20	20	20	20	yr
Capital costs	655,458,322	973,365,114	1,055,830,770	1,458,738,022	US$/(30 yr)
Equivalent full load period	6,412	6,412	6,386	6,386	h/a
Electricity generation	19,236,960,000	19,236,960,000	42,147,864,000	42,147,864,000	kWh/(30 yr)
Insurance	0.5%	0.5%	0.5%	0.5%	of investment/yr
Insurance	46,545,000	69,120,000	74,976,000	103,587,000	US$/(30 yr)
O&M	0.006	0.008	0.003	0.006	US$/kWh$_e$
LEC	0.042	0.062	0.030	0.043	US$/kWh$_e$

Table 2-8: Technical assumptions and cost predictions for central receiver plants with 12 h thermal storage capacity; LEC without taxes and tax credits (LBST derived from [S&L 2003])

Parabolic through as well as central receiver plant concepts are potential reference concepts.

Table 2-9 shows the assumptions Sargent & Lundy and SunLab base their cost reduction calculations on.

	Sargent & Lundy (S&L)	SunLab
Parabolic trough	2.8 GW_e	4.9 GW_e
Central receiver	2.6 GW_e	8.7 GW_e

Table 2-9: Allocated cumulated plant deployment between 2002-2020 for cost reduction [S&L 2003]

Further assumptions and investigations for cost reductions concerning the specific scenarios are presented below in chapter 2.2.3 Learning curves.

Table 2-10 compares the major technology and cost assumptions and predictions of both technologies for mid and long term.

	Parabolic trough	Central receiver
Capacity factor	~ 57 %	~ 73%
Full load hours	~ 5,000 h/yr	~ 6,400 h/yr
Mid term (~ 2010)		
Electricity output	150 MW_e	100 MW_e
LEC SunLab S&L	 0.058 EUR/kWh_e 0.073 EUR/kWh_e	 0.042 EUR/kWh_e 0.062 EUR/kWh_e
Long term (2020-2030)		
Electricity output	400 MW_e	220 MW_e
LEC SunLab S&L	 0.043 EUR/kWh_e 0.063 EUR/kWh_e	 0.030 EUR/kWh_e 0.043 EUR/kWh_e

Table 2-10: Reference data for SOT: technological assumptions and cost predictions for parabolic trough and central receiver [S&L 2003]

Any further terrestrial scenario evaluation in the next chapter concerning SOT plants is purely based on the central receiver concept. This concept was selected due to its higher solar capacity factor respectively full load hours per year, and as a result due to its lower electricity cost. Figure 2-50 summarizes the relevant reference data required for further scenario evaluations. Further cost reduction potentials and learning curves are considered and discussed in chapter 2.2.3. Specific additional plant sizing like increase of electricity storage capacity is performed in the following individual chapters for the specific scenarios.

Power Supply		**220 MW_e**
LEC:	**Min.**	**0.030 US$ / kWh_e (@9.7 GW_e installed)**
	Max.	**0.042 US$ / kWh_e (@2.6 GW_e installed)**
Land Area:		**14 km² / Plant**
Operation:		**~6,400 full load hours per year**

Figure 2-50: Reference system for 2030: central receiver with 13 hours thermal storage; cost data referring to the n^{th} system [S&L 2003]

2.2.3 Learning curves

Learning curves define how unit costs decrease with cumulative production. The specific characteristics of the learning curve are that the cost declines by a constant percentage with each doubling of the total number of units produced. The learning curve may be mathematically expressed by Equation 2-3.

$$C_N = C_1 \cdot N^b$$

Equation 2-3: Basic formula for learning curves

where

C_N Cost of the Nth unit

C_1 Cost of the 1^{st} unit

N Cumulative number of units

b experience index which gives the cost reduction at each doubling of production volumes

The cost reduction is ($1-2^b$) for each doubling of cumulative production where the value (2^b) is called the progress ratio (PR). The progress ratio is used to express the cost reductions for the different technologies. The experience index can be calculated from past experience according to

$$b = \frac{\ln(PR)}{\ln(2)}$$

Where this experience doesn't exist it must be estimated by means of an 'educated guess' in analogy to similar technological manufacturing processes.

For wind energy a progress ratio of about 0.82 has been observed during the early development (1980 to 1995). Various studies on learning curves from actual data suggest that a progress ratio of 0.82 has bee observed for photovoltaics (PV) which would lead to an experience index of about -0.29. In [S&L 2003] the progress ratio for 148 m^2 heliostats has been indicated with about 0.93 which leads to an experience index of b = -0.10.

Table 2-11 and Figure 2-51 show further allocated learning curve effects for the selected central receiver plant for 2030. Major cost reduction potentials are only identified for the heliostat field.

Installed capacity	1	10	20	100	200	1000
Structures & improvements	7.2	7.2	7.2	7.2	7.2	7.2
Heliostat field	372.5	294.9	274.9	233.5	217.7	184.9
Receiver	34.4	34.4	34.4	34.4	34.4	34.4
Tower & piping	24.3	24.3	24.3	24.3	24.3	24.3
Thermal storage	57.2	57.2	57.2	57.2	57.2	57.2
Steam generator	9.3	9.3	9.3	9.3	9.3	9.3
Electric power block	83.6	83.6	83.6	83.6	83.6	83.6
Master control system	1.6	1.6	1.6	1.6	1.6	1.6
Balance of plant	9.9	9.9	9.9	9.9	9.9	9.9
Engineering, Management etc.	46.8	40.7	39.2	36.0	34.7	32.2
Land	0.0	0.0	0.0	0.0	0.0	0.0
Contingency	42.1	38.2	37.2	35.1	34.4	32.7
Contingency cost reduction	0.0	0.0	0.0	0.0	0.0	0.0
Risk pool	0.0	0.0	0.0	0.0	0.0	0.0

Table 2-11: Learning curve effects for 220 MW_e central receiver depending on installed capacity: split of investment cost in EUR/plant

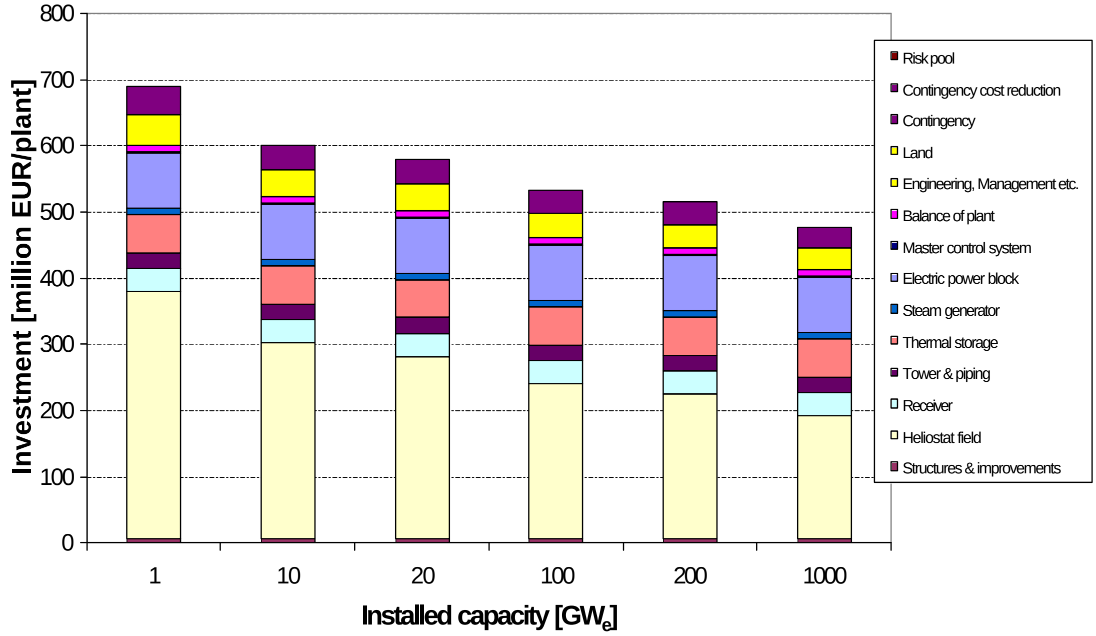


Figure 2-51: Learning curve for central receiver: cost reductions of central receiver depending on installed capacity

3 SPACE SYSTEM ARCHITECTURES

3.1 Previous studies and concepts

3.1.1 Early work

In this Section, we provide a brief historical background of the power-from-space concept: in so doing we identify and flag those works that can serve as reference description for the scenarios under discussion. Similarly, we spell out the limits adopted for the present case. First, one can distinguish between productive and non-productive systems. In the first class belong those items that actually generate electricity in the space environment, before transmitting power to Earth, while the second class includes passive items (reflectors), used to redistribute power, generated either on Earth or in space.

One can summarize the chronological evolution of the power-from-space concept with respect to productive systems as briefly as follows:

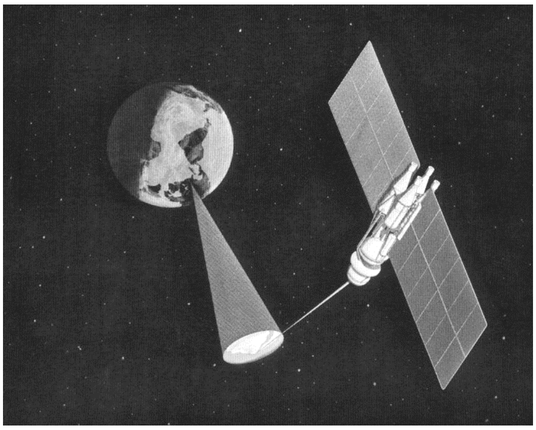
– Peter E Glaser originates the concept in his 1968 Science article (Glaser, 1968), and in 1973 receives a US patent therefor (Glaser, 1971).

– In the early 1970s, NASA begins to study and review the SSPS, and includes power from space in the 1976 "Outlook for Space" review.

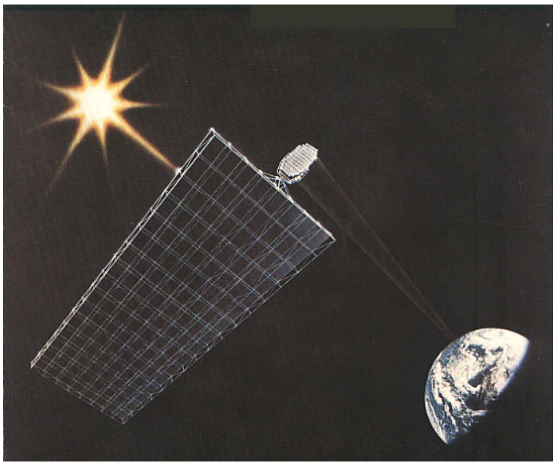
– Researchers at the Georgia Technical Institute published in the spring of 1973 (one of) the first study of a Space Nuclear Power Station (Williams & Clement, 1973). The study estimates a 9,070-t system with $10-billion recurring costs for a 10-GW power level and 40-year fuel loading (picture a) in Figure 3-1).

– Towards the mid-1970s, Prof O'Neill introduces the discussion of the use of lunar materials for SPS manufacture (O'Neill, 1975), stimulating the organization of one of the most vibrant research communities around the theme.

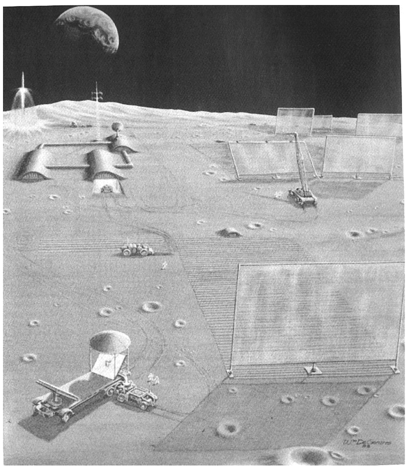
– Between 1976-1980, a first, larger-scale assessment of the space power concept occurs in the US, in the form a multi-agency study and review activity. The Department of Energy (DoE) leads the CDEP effort that, with NASA support, defines the SPS Reference Concept, an 80,000-t system delivering 5-GW power to the terrestrial grid (picture b) in Figure 3-1). In 1981, both the Congress Office of Technology Assessment (OTA) and the National Research Council (NRC) publish their own assessment of the CDEP effort. NRC appears critical of the Reference Concept's economics, and government-supported research essentially stops in the US.



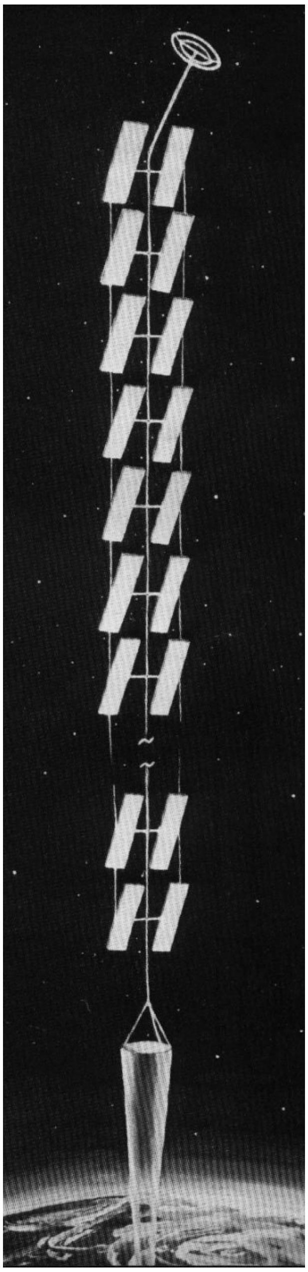
a) Space Nuclear Power Satellite concept [Williams 1973]



b) DoE/NASA CDEP Reference Concept (NASA)



c) Elements of the Lunar Power System [Criswell 1991]



d) The Gravitationally-stabilized SPS concept [Cantafio 1977]

Figure 3-1: Solar space concepts I (pictures: a-d)

– Cantafio, Chobotov & Wolfe (1977) introduce the solid-state, gravitationally-stabilized SSPS, also a geostationary orbit, 5-GW power level system with a 20,000-t mass and 20-year lifetime (picture d) Figure 3-1). The GSSPS will later inspire John Mankins for the Sun Tower concept.

– First ideas for an integrated solar power satellite (picture f) Figure 3-3) are published by Pospisil (1979). The concept receives a wider discussion much later, by Landis & Cull (1991).

– In the mid-1980s, merging work on space materials processing and robotics, David Criswell and Robert Waldron introduce the Lunar Power System concept that uses the Moon itself as base platform (picture c) Figure 3-1), but requires a fleet of geocentric-orbit reflectors to distributed the power beamed from the lunar surface (Criswell & Waldron, 1985).

– Throughout the 1980s, Japanese researchers – in particular Prof Makoto Nagatomo, Prof Nobuyuki Kaya, and Prof H Matsumoto, with their colleagues and coworkers -- continue studies and experimental activities related power from space development, including ionospheric probing on suborbital rocket flights. Around 1990, ISAS announces the SPS-2000 prototype idea (Nagatomo & Itoh, 1991; Figure 3-2). SPS-2000 was defined as a 10-MW power level satellite on 1100-km equatorial orbit, sequentially delivering power to sites near the equator: its limited size kept the rectenna peak power density down, to 9 W/m^2 (which stimulated Japanese research on low-power rectenna schemes). It would have system mass of the order of 250-t and the target cost was set at some 9 billion Yen (100 million EUR), excluding launch costs.

– In 1996 Prof Kaya re-introduces the "sandwich" SPS concept (Kaya, 1996) studied as part of the US Department of Energy study in the 1970s.

As for the non-productive systems, one can list following milestones:

– the discussion of the orbital Sun light reflector concept by Oberth (1923)

– the introduction of the power relay satellite (PRS) concept by Ehricke (1973)

– the extensive studies by Krafft Ehricke, mostly between 1970-1976, suggesting and evaluating orbital solar reflectors for illumination (Lunetta) and power (Soletta) uses on ground

- NASA studies Solares, a constellation of orbiting mirror to boost ground-based solar power production (s.e.g. Billman & Gilbreath, 1978)
- Criswell's Lunar Power System includes orbital reflectors for beams redirecting (Waldron & Criswell, 1985)
- the power reflector satellite concept resurfaces, taken up, e.g. by RW Bussard (Wallace & Bussard, 1991)
- the NASA "Fresh Look" team looks at MEO constellations of space power stations, and includes reflector satellites (in particular using reflectarray technology) for power distribution, and recommends 10 MW LEO demonstrator.

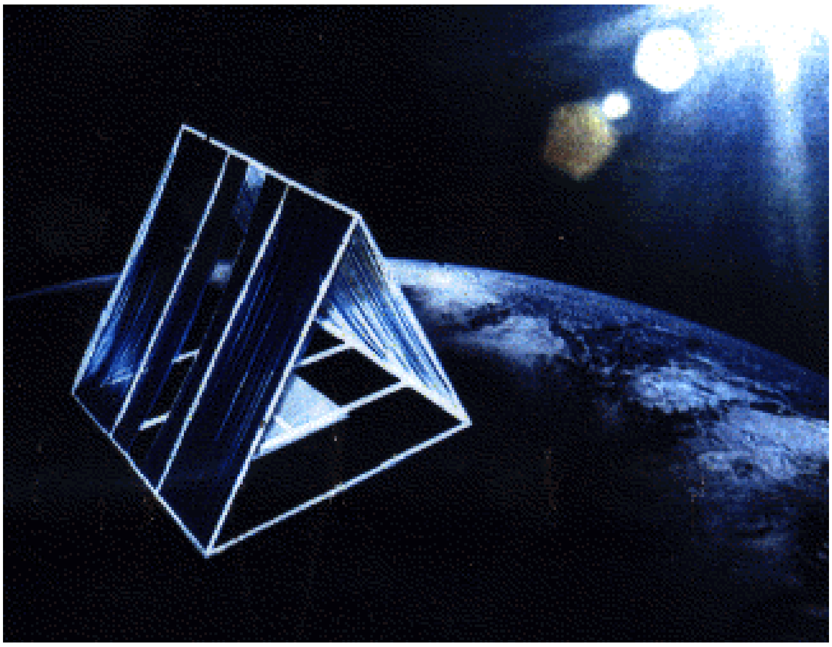


Figure 3-2: Solar space power concepts II: A typical configuration of SPS 2000 (e): the square in the Earthward face of the satellite structure represents the transmitting antenna (ISAS picture)

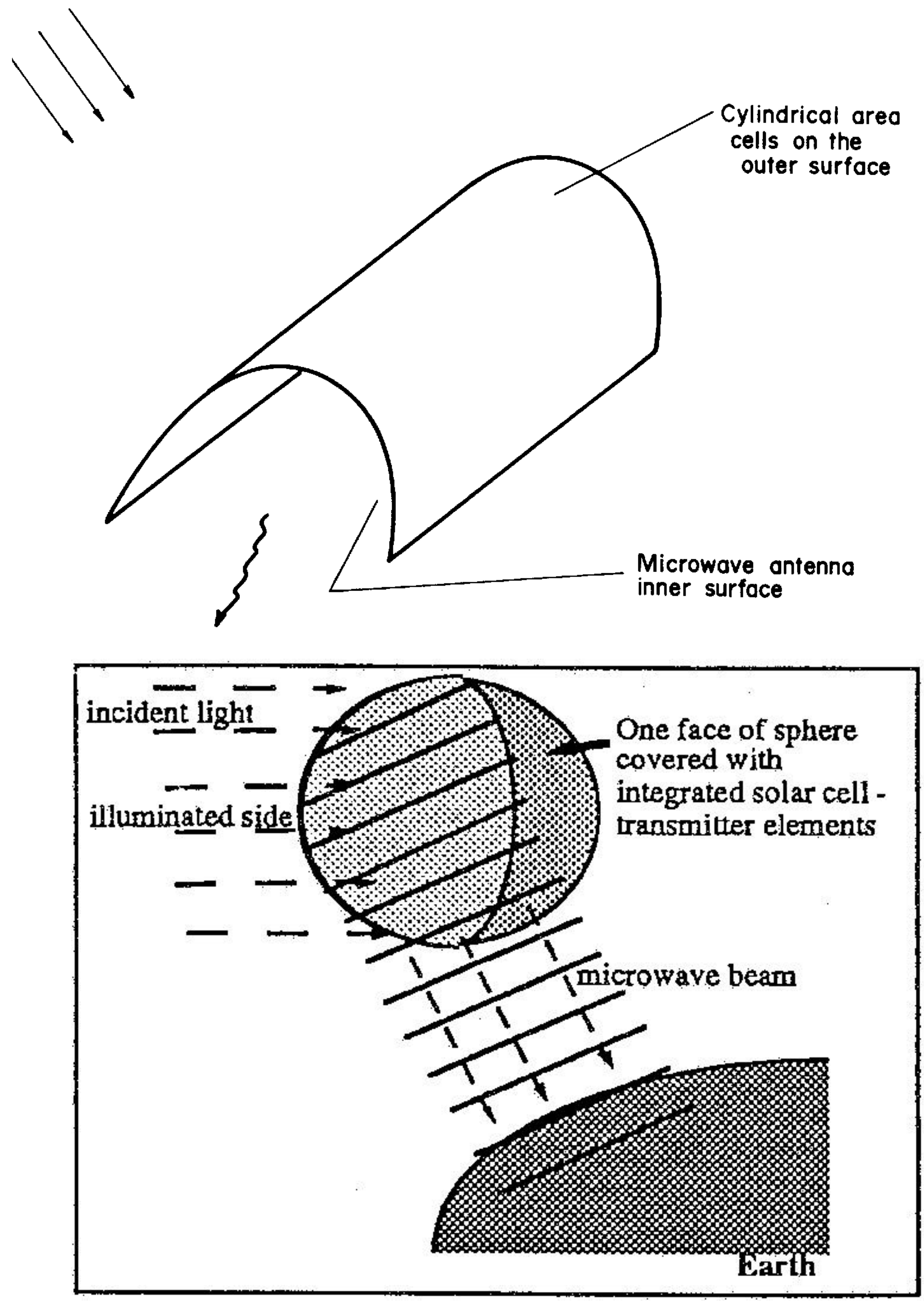
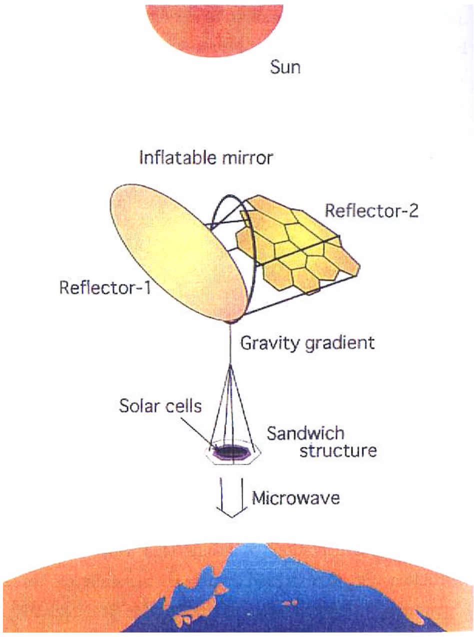
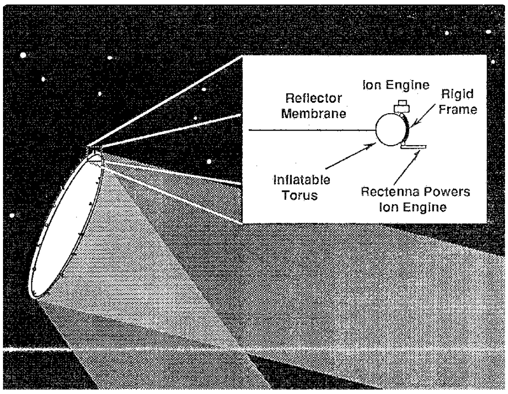
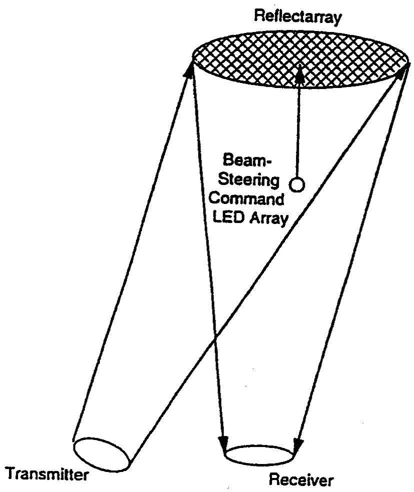


Figure 3-3: Solar space power concepts III: Schemes of principle for integrated solar power satellites (f): (top) from Pospisil (1979) and (bottom) from Landis & Cull (1991)



g) Configuration of a sandwich SPS using a solar concentrator (from Kaya, 1996).





h) Evolution of power relay satellites: (above) a passive, focusing system (from Wallace & Bussard, 1991) and (at right) a beam-steering reflectarray proposed in the Fresh Look study (from Feingold, Stancati, & al, 1997).

Figure 3-4: Solar space concepts IV (pictures: g-h)

3.1.2 Recent and current activities

One can list a number focused activities on the subject of power supply from space facilities, deployed after the mid 1990s.

NASA Fresh Look at the Feasibility of Generating Solar Power in Space for Use on Earth.

During 1995-1997, NASA conducted a study from which approaches emerged that appeared to be much more viable — technically and economically — than past systems designs.

NASA SSP Concept Definition Study

During 1998 NASA conducted a $2M SSP Concept Definition Study (CDS).

NASA Space Solar Power (SSP) Exploratory Research and Technology (SERT)

The approximately $22M SERT program was conducted in FY 1999-2000, and included systems studies, technology research tasks, & technology demonstrations.

NASA/NSF Workshop on Autonomous Construction & Manufacturing for Space Electrical Power Systems, Arlington (Virginia), April 4-7, 2000.

Final Report edited by George Bekey, Ivan Bekey and David Criswell.

NRC's Aeronautics and Space Engineering Board: Committee for the Assessment of NASA's Space Solar Power Investment Strategy (2001): Laying the Foundation for Space Solar Power: An Assessment of NASA's Space Solar Power Investment Strategy.

Report of an independent peer review of NASA’s SSP R&T road maps, conducted by a National Research Council assessment panel chaired by Richard J Schwartz.

NASA SSP Concept and Technology Maturation (SCTM)

NASA-NSF-EPRI Joint Investigation of Enabling Technologies for SSP (JIETSSP).

During FY2001-2002, NASA continued SSP work, with additional emphasis on

- System modeling tools
- Critical technology research topics
- Technology flight demonstrations

A multi-agency program was announced in 2002. This effort led to a number of Technical Interchange Meetings such as: Space Solar Power Concept & Technology Maturation (SCTM) Program Technical Interchange Meeting (TIM), Cleveland (Ohio), September 10-12.

In addition, several conferences have been dedicated to the subject of obtaining power from space, including:

– the CASI/SEE "SPS-97 Conference: Space and Electric Power for Humanity," Montreal (Canada), August 24-28, 1997.

– a Special Session of Commission H on "Power Transmission from Solar Power Stations -- Technological, Environmental & Biological Aspects," during the XXVII URSI General Assembly, Maastricht (The Netherlands), August 17-24, 2002.

– the First Japan-United States Joint Workshop on Space Solar Power System -- "JUSPS '03," Kyoto University, Kyoto (Japan), July 3-4, 2003.

	W&C 73	CDEP-DoE 80	CCW 77	ISAS-SPS2000	NASA-Freshlook
Power output [MW]	10,000	5,000	5,000	10	1,000
Operation life time [yr]	?	40	20	10	
Total weight [t]	9,070	80,000	20,000	250	38,400
Specific weight [g/W]	1	16	4	25	38
Total cost	$ 10 bill	n.a.	n.a.	¥ 9 bill excluding launch	$ 9,4 bill
Specific cost	1 $/W	n.a.	n.a.	900 ¥/W	1 $/W

Table 3-1: Comparison of concepts at aggregated level

3.2 Selected reference concepts

In the course of this chapter, focus is put on the selection of the most promising concepts for this study.

The framework set by the Statement of Work [Anon 2003] leads to the decision to exclude from the present study's consideration any space power station concept based on the utilization of non-terrestrial materials or space manufacturing, as well as the use of nuclear energy sources. Also, because of the requirement to rely on previous development work – exemplified by the list of reference documents in the SOW and implemented through the budget limits – primary attention in the search for reference concepts goes to those that resulted from relatively large investigations, leaving aside others that received more cursory discussion.

To assess whether these limitations (against non-terrestrial materials and integrated designs) are fair or wise would in any case require another study.

Then, the foundations for the present work can only come from the CDEP and the "Fresh Look" reports. Other results, in particular from the SERT projects may find use, largely depending on the degree of detail made available in the documentation obtainable.

Finally, building on the existing base of research and again considering the framework given, it appears that the use of plants located in geostationary orbit (GEO) represents the most economically sensible approach, as well as the only one that may become possible under the constraints.

The following two technical concepts are selected for scenario building, depending on the scenario specific requirements:

– MEO Sun Tower without electrical storage

– GEO Solar Disk with two electrical storage options

A basic introduction into these two concepts is given below (chapter 3.2 3.2.1 and 3.2.2. A further more detailed description of the reference concepts for each scenario including electrical storage facilities is described in chapters 5.2.1 and 6.2.1.

3.2.1 MEO Sun Tower as reference

The "Sun Tower" space solar power concept was originally defined to reduce the development and life cycle cost of an SPS, while at the same time broadening market flexibility. The system concept included a modular space segment and an evolutionary approach, calling for initially deployment in LEO, and successive migration to an operational orbit. For the prescribed regional approach, we selected a small constellation on medium-altitude orbits (MEO) above 6,000 km, inclined some 30-50° (Figure 3-5). In such a system, a satellite/ground receiver 'pair' is sized to 250 MW scale, with four satellites assumed as required to maintain constant power at that level – following the examples given in the „Fresh Look" Study. Figure 3-6 illustrates the typical MEO orbital architecture.

The Sun Tower design was conceived for keeping the development cost low, through its extensive modularity; the relatively small individual components can be ground tested with no new facilities and demonstrated in a flight environment with a sub-scale test. Manufacturing can be 'mass production' style from the first satellite system. Also, no concept-unique ETO transportation system is required, beyond that necessary to achieve extremely low launch costs (on the order of $200 per kg), with payloads greater than 10 t.

The in-space transportation elements must meet two functions: (1) transport of the Sun Towers from LEO to the MEO orbits (this may be an inherent function of the SPS, e.g. by using SEPS), and (2) transport replacement elements to the operational orbit and return of replaced elements for de-orbit.

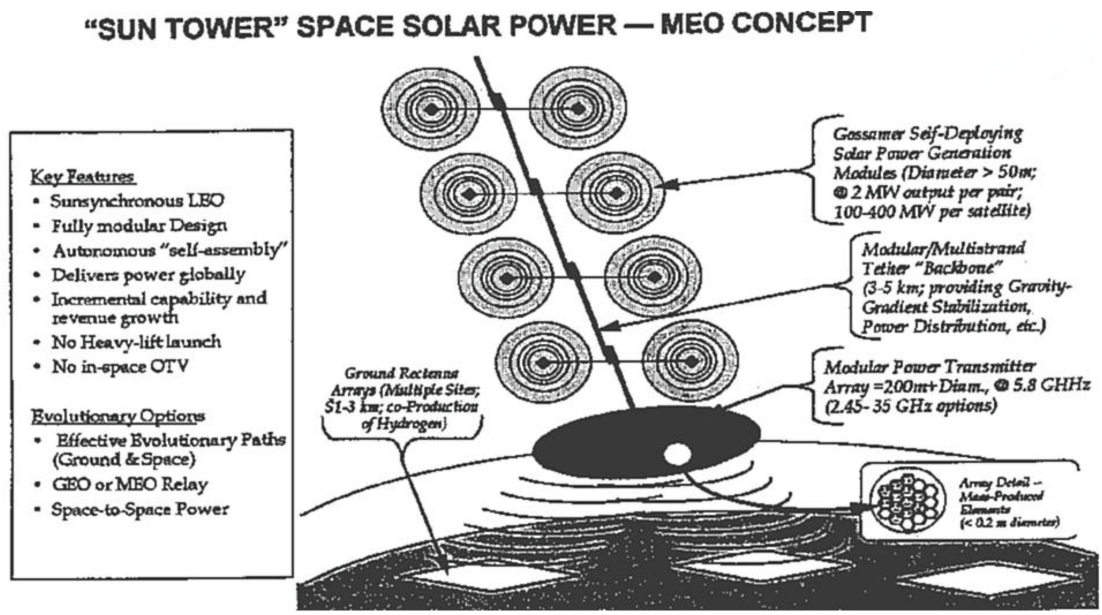


Figure 3-5: The Sun Tower SSP Space Segment Concept [NASA 1997]

The "Sun Tower" space segment unit consists of a medium scale, RF-transmitting space solar power station of the gravity gradient-stabilized type. Each satellite includes a set of pairs of solar collectors and a transmitter array. Sunlight-to-electrical power conversion is modular and deployable in "units" of approximately 75 m diameter, and a net output of 1.3 MW (electrical). The primary technology option is a gossamer-structure, including a concentrator and advanced PV cells at the focus. Part of the assumptions is that, in dimensioning a solar array, the End-Of-Life (EOL) performance is used, as is general practice, with any solar cell degradation translating into some penalty in terms of mass or cost, that is implicitly accounted for in the SPS concept budgets. The collection systems are further presumed to be always sun facing, attaching regularly in pairs along the length of a structural/power transmitting tether to the back-plane of the transmitter array; they must be capable of rotating (nodding) along a single axis while the satellite maintains a continuous – one rotation per orbit – roll maneuver to maintain constant sun-track.

The concept transmits power at 5.8 GHz, at a level sufficient to produce 250 MW output from a ground-based planar rectenna. Total beam-steering capability is 60° (±30°): a single transmitting element would have an hexagonal surface, less than 4 cm across, with a nominal 12.5 W input power level @ 80% conversion efficiency -- yielding an output of about 10 W. These elements are pre-integrated into 'sub-assemblies' for final assembly on orbit. The transmitter array is then an 'element and sub-assembly -tiled plane,' essentially circular, and approximately 260 meters in diameter, with a fractal matrix power distribution grid on the backplane, with a total thickness of about 1 m.

Heat rejection for power conversion and conditioning systems in assumed to be modular and integrated with power conversion systems; for the transmitter, it is integrated in the 'backplane' of the array. Power transmission lines from the single, central tether attachment point to the back-plane are assumed to be integrated with the modular sub-assemblies of the array.

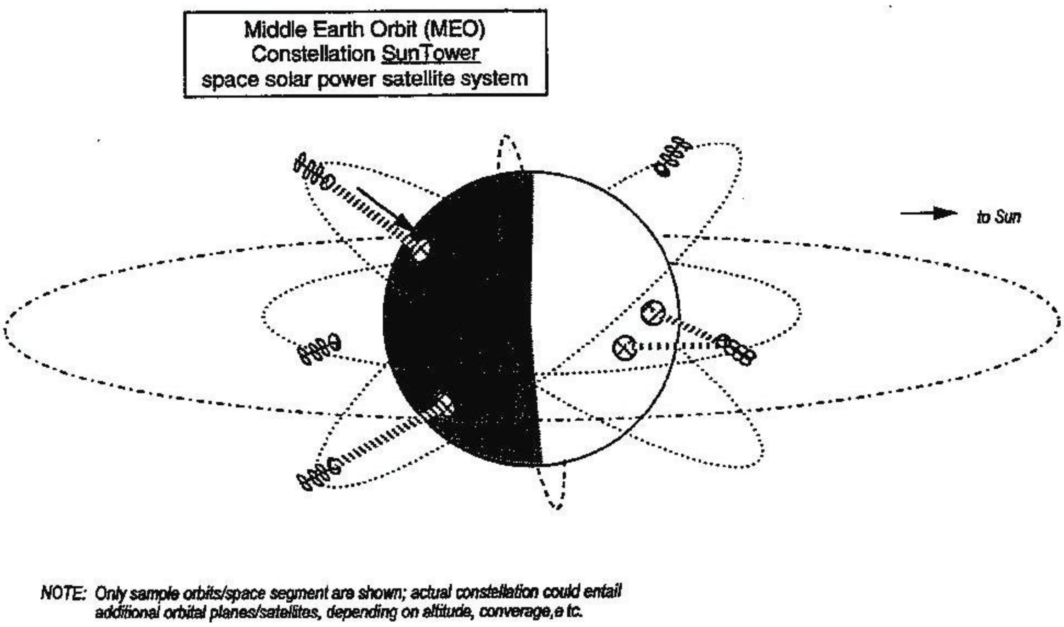


Figure 3-6: The MEO Sun Tower Concept Architectural [NASA 1997]

The MEO constellation does require a low-cost (possibly space-based) orbital transfer vehicle to transport system elements from LEO to the operational orbit. Furthermore, Feingold and co-workers [NASA 1997] assumed that the launched systems include modular assembly-support items that might consist of mechanical elements inherent in the structure, or of a more sophisticated and mobile, self-contained robotics approach.

The ground segment was assumed to build on nominal ground receivers using planar rectennae of approximately 4.5 km diameter, with direct electrical feed into the commercial power utilities interface. This would mean quite low power density over the receivers (average of 15.7 W/m^2).

3.2.2 Solar Disk as reference

The "Solar Disc" space solar power concept involves an extensively axisymmetric, modular space segment which 'grows' in geostationary Earth orbit (GEO), and thus can provide an early 'on-line' capability at a reduced power level. A single satellite/ground receiver 'pair' would be used for this early application; this pair can be sized according to the specific market, ranging from approximately 1 GW to 10 GW scale. Figure 3-7 summarizes the Solar Disc system concept, while Figure 3-8 shows the Solar Disc architectural context.

This concept, owing to its extensive modularity, also entails relatively small individual system components that can be developed at a moderate price, ground tested without new facilities, demonstrated in a flight environment with a sub-scale test, and go rapidly in a 'mass production'-style manufacturing. Again, as for the Sun Tower, no unique ground launch infrastructure is required, beyond that for achieving the required low launch costs (see chapter 7.3.2).

On the other hand, Space Disc requires a unique in-space transportation system, which must provide an extremely affordable transfer from LEO (where the initial system deployment occurs) to GEO. Again, it was assumed that the launched systems include modular assembly support systems -- either mechanical or robotic.

The "Solar Disc" concept uses single, large-scale, GEO-based, RF-transmitting space solar power satellites, in the shape of a large disc, ranging up to 9 km in diameter. The outer portion of the disc is a thin-film PV (TFPV) array, rotationally stabilized and continually Sun-pointing. These elements are anticipated to be highly modular, and deployable in "units" that represent a single concentric sing of uniform width.

The center of the disc is occupied by a free-turning transmitting antenna and feed system that is electromagnetically coupled but mechanically decoupled from the rotating outer disc so that it can maintain a continuous Earth-pointing orientation. The scheme in Figure 3-7 shows that, to eliminate periods during which the outer disc would block the transmit beam, two separate transmitting arrays (or reflectors, if an RF rather than DC feed is employed) are used. Each transmitting area is approximately 0.5-1.5 km in diameter, depending on the power requirement. These arrays (or reflectors) are offset from the central axis by a long (approximately 1 km) tether that provides a degree of gravity gradient stabilization for the inner, Earth-pointing structure.

The concept is assumed to transmit at 5.8 GHz from its operational GEO location, with a total beam-steering capability is 20° (±10°), which provides greater than full hemispheric coverage from GEO. Although the transmitting arrays/reflectors must be assembled at their final projected site, transmitter assembly and RF feeds are modular and can be incrementally added.

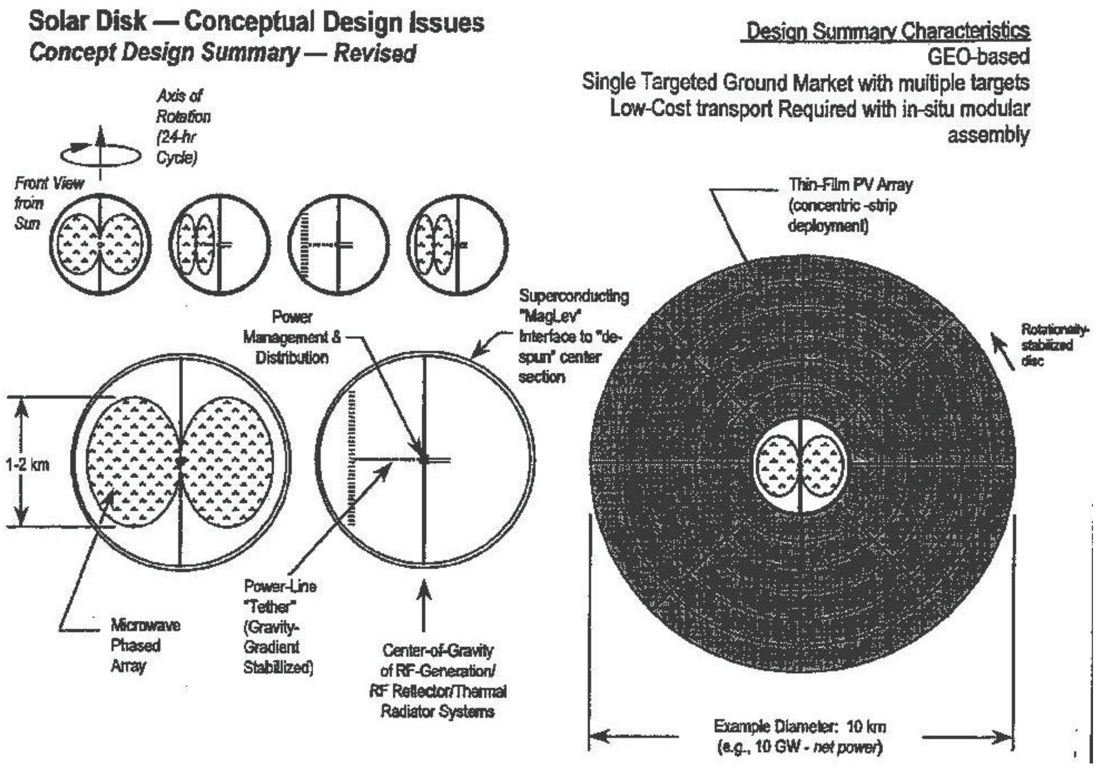


Figure 3-7: The Solar Disc SSP Space Segment [NASA 1997]

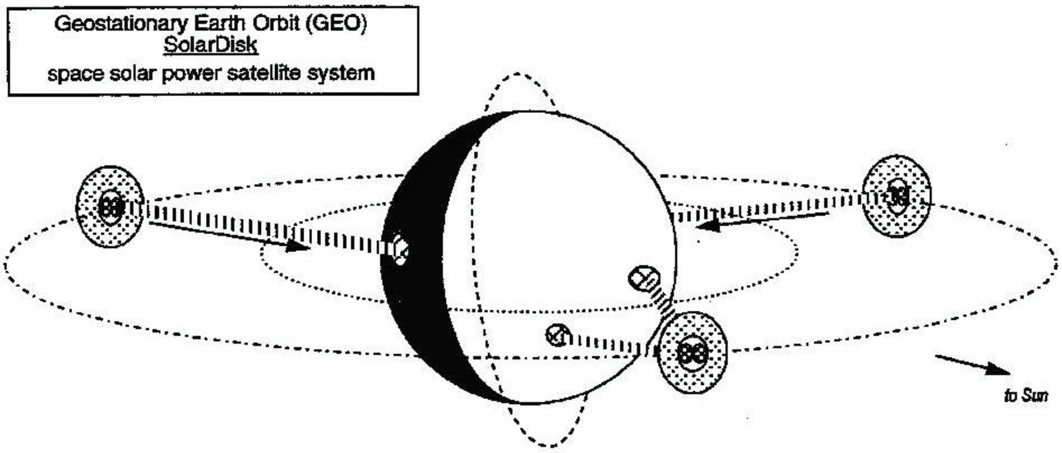


Figure 3-8: The GEO Solar Disc Concept Architectural Context [NASA 1997]

The ground segment's nominal ground receiver is a 10+-km diameter site, with direct electrical feed into the commercial power utilities interface. Multiple ground sites (e.g. on order 10-20) could be served from a single Solar Disc SPS, with time-phased power transmission. For a basic, single-beam antenna, the beam will then stop transmitting to one antenna before it starts to transmit to another. Though the output of the beam can be reduced very rapidly (e.g. to zero in 450 ms), in practice the output of the microwave power beam would be reduced more slowly in time with the requirement of the terrestrial electric utility. Transmission to a new rectenna would start with acquisition of the new rectenna's pilot beam at the satellite, which would use it to control the phasing of the transmitting antenna elements. Power would build up as fast as the utility requires.

For primary power, no ground-based energy storage system would be required.

3.2.3 Assumptions for power transmission via microwave

The efficiency (and the corresponding losses) in the power transmission chain form a major factor not only in the definition of an SPS architecture, but also in its overall significance as an energy supply system. Contemporary data provided by [Marzwell 2000] are listed in Table 3-2, showing little advancement over those assumed in the CDEP Reference Study. One notes that the largest power losses (after the photovoltaic conversion, occurring upstream of the first entry in Table 3-2) occur in the microwave generators (27% of nominal power) and in the diplexing filters (50%). It is understood that these elements, under the „Fresh Look" assumptions, are distributed (solid state) devices, and accordingly have up to 1 km^2 area from which to operate, i.e. requiring a power rejection of about 3.08 kW/m^2 (corresponding to a 490-K single, untextured radiating surface).

The reference study [Anon 1979] set the rectenna's minor semi-axis at 5 km, for 5 GW of power delivered: this is equivalent to a basic average extracted power density of 63.66 W/m² – further decreasing with latitude. The rectenna site proper was extended by a 0.7-km wide exclusion area, to let the power density drop further down to less than 1 W/m². As reported, e.g. [Redding 1977] or [Brown 1979], the power density over the rectenna's aperture varied from a peak of 230 W/m² down to 10 W/m² at the rim, this last value corresponding to one-tenth of the US continuous-exposure standard; the more stringent standard in the Former Soviet Union – 0.1 W/m² (see discussion in chapter 10.2.2c) – is reached 3 km from the aperture's edge.

An issue investigated in the period of the CDEP concerned the potential for nonlinear heating of the ionospheric medium by the microwave beam: the critical point was predicted to be in the range of 150-300 W/m², raising the possibility that the SPS beam could cause thermal runaway [Brown 1979]. [Mankins 1999] report as „probable only limit" the RF breakdown voltage levels in the beams at stratospheric altitudes, i.e.:

– 50 kW/m², 1 GHz, 55 km

– 8,000 kW/m², 10 GHz, 38 km

Element	Efficiency	Power	Heat
S/c DC-EM conversion efficiency	0.90	2.67	0.27
EMC & diplexing filters	0.794	2.40	0.50
Subarray aperture efficiency	0.95	1.90	0.09
Subarray failures	0.96	1.81	0.07
Amplitude errors, taper quantization	0.986	1.74	0.03
Phase errors	0.97	1.71	0.05
Beam steering scan loss	0.977	1.66	0.04
Beam coupling (avg) efficiency	0.918	1.62	0.13
Propagation impairements	0.933	1.49	0.10
Polarization mismatch	0.999	1.39	0.00
Rectenna aperture scan loss	0.999	1.39	0.00
Rectenna elements failures	0.99	1.39	0.02
Rectenna aperture efficiency	0.95	1.37	0.06
EMC filtering	0.891	1.31	0.15
Ground EM-DC conversion efficiency	0.86	1.16	0.16
Required power output to grid		1.00	

Table 3-2: Power transmission efficiency [Marzwell 2000]

An rough average value estimate basing on the power distribution data from [Redding 1977] yields 97 W/m². With the assumed values for the efficiency of the energy collection, the rf-dc power conversion, and for the grid interface (86%, 87%, 99%, i.e. 74% total; or as revised: 88%, 90%, 99%, 78.4% total) the corresponding output value works out at 71.8 (or 76.0) W/m², or 13-19% higher than indicated by the global approximation.

Current efficiency estimates seem to come down to 72% (using the data from [Marzwell 2000]. If we take the average power density over the rectenna at 97 W/m², the average output would then amount to almost 70 W/m². However, the 5-GW Solar Disk is associated with a 19.63 km² rectenna, leading to an average power extracted of 254.7 W/m², which would correspond to average power density above the rectenna of 353.8 W/m², or 3.6 times higher than in the CDEP scenario.

This level seems too optimistic, when set against the above-mentioned standards. However, to reflect the advantage of operating at a higher frequency, the average power in the beam above the rectenna was arbitrarily set at 200 W/m²; at the same time, the width of the exclusion area was increased to 1 km. Actual power density distributions – above and beyond the actual collecting area – will depend on the illumination functions over the transmit antenna aperture, and one can very reasonable expect that a large freedom exists to adapt those patterns to minimize exposure values on ground.

Power transmission between satellite and ground based rectennae via microwave is physical best described as a diffraction on a circular aperture [Sizmann 1978]. A principle distribution of microwave intensity is depicted in Figure 3-9.

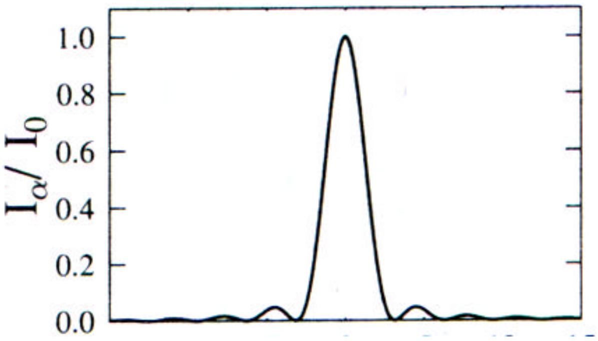


Figure 3-9: The principle intensity distribution of microwave irradiation is considered as a diffraction on a circular aperture [Stöcker 1994]

Figure 3-9 shows that side-lobes may have to be taken into account when designing a space based solar power system and rectennae respectively.

3.3 Flexible operation of solar power satellites and rectennae

A space-based power supply system comprising one satellite and one rectenna supplying continuous power is the simplest case to analyze economically, and it has received most attention in the "Fresh Look" study [NASA 1997], the US Department of Energy's 1970s "Reference System" study [DOE 1980], and elsewhere. However, in reality, rectennae and solar power satellites would be separate facilities which could be operated in a number of more flexible ways than simply supplying base load power. These possibilities would increase as the total number of satellites and rectennae in operation increased.

The Fresh Look study refers to the concept of a "Planetary Power Web", which is described as "...a space solar power concept which assumes a mature network of space solar power assets... and ground-based receivers. …A key use of the Power Web concept would be for providing peak power or load leveling on an intercontinental basis. This could be accomplished using solar power generated by the Power Web system elements or by the relay of power generated by other sources..." [NASA 1997, pp 49-50].

A similar idea, the desirability of flexible operation of a space-based solar power system, was discussed during the US DOE study [DOE 1980]. For example, Europeans Shelton and Franklin noted that continuous supply represented only about 20% of electricity output in Britain, and stated: "SPS acceptability would be greatly enhanced if it were more flexible, and possessed some measure of capability for load-following" [Shelton 1980].

Electricity supply companies, which will determine the conditions under which space-based solar power might be used, have a similar view. Donalek and Whysong state the economic advantages of operating space-based systems with a high load factor, but they point to the physical difficulty of utilities operating nuclear and coal plants on non-base load schedules (in order to accommodate solar power satellites) since they suffer physical damage from repeated thermal cycling [Donalek 1978]. Kubitz and Moss suggest that progress towards using space-based power would involve a cautious, step-by-step process, starting with purchases of power, then involving installing equipment to connect a rectenna to the grid, thirdly building a rectenna, and only fourthly possibly investing in a satellite itself [Kubitz 1980].

EU electricity demand in 2030 is discussed in Section 4.3.4. The winter maximum is forecast in Figure 4-5 as 570 GW, and the summer minimum is forecast Figure 4-6 as 255 GW. Consequently demand for continuous electric power would be some 45% of the maximum. In this case, 500 GW of space-based solar power would be nearly twice the demand for continuous power in Europe.

One possible strategy would be to export power to countries outside Europe, as discussed in Section 8.3.3 below. Alternatively, excess supply capacity could be used to charge storage systems to reduce the peak capacity needed; however this would incur additional cost and losses, and so would be feasible only if the system was economic at significantly less than 97% load-factor, as discussed in Section 8.2.4. A third alternative is to use space-based solar power supply systems for flexible supply of non-base load power.

As discussed in Section 8.3.3b), a European space-based solar power system of 500 GW capacity would be likely to be accompanied by similar capacity in both Asia and America. Such a system would be sufficiently large and mature to operate as a "planetary power web" in which the system's potential operational flexibility would be exploited to supply higher-priced non-base load power in addition to continuous power supply. In order to assess the feasibility and potential of such a system, it is necessary to analyze the conditions under which non-continuous operation could be economic; a method of performing this analysis is demonstrated next, taken from [Collins 1991].

3.3.1 De-coupled satellite and rectenna operation

From the technical point of view, delivery of microwave power from space to Earth would be uniquely flexible; the direction of a multi-GW microwave beam could be switched rapidly, thereby moving its "footprint" on the Earth by thousands of kilometers. Kaupang describes ways in which power delivery to a rectenna could be controllably reduced to zero in less than 1 second [Kaupang 1980]. For electricity supply, ramping power output up and down over a period of minutes or even longer would generally be preferred by electricity grid managers. Consequently a space-based solar power station could deliver power in rotation to two or more different rectennae in response to utilities' changing demand.

An important constraint on this flexibility is the economic need to keep the load-factors of both rectennae and satellites high enough to be profitable. However, in the Fresh Look study [NASA 1997], the cost of the rectenna is estimated as being only some 7.5% of the total system cost. Because of this, rectennae would be much less tightly constrained to achieve high operating load-factors than satellites. That is, although it would not be profitable to operate an orbiting solar power plant with a load-factor much less than the maximum possible, this would not necessarily be true of rectennae. Moreover, satellite operators would have more interest in revenue maximization than in load-factor maximization per se, and electricity prices are not constant. The unique capability of space-based systems to transmit power to rectennae over a wide range of latitude and longitude would enable them to deliver power to more than one rectenna at lower load-factors of the rectennae than of the satellites.

Calculation of the cost of non-base load power supplied by a space-based system therefore requires the rectenna and satellite to be treated as separate facilities. In this case, their respective contributions to the total cost of power would depend primarily on their respective load-factors, since most of their costs would be fixed costs. Analyzing their costs separately in this way enables the feasibility of various operating schedules to be understood. NB for these calculations the cost of the satellite must include all costs, including transportation, construction, maintenance etc, and the rectenna cost must include the cost of linking to the electricity distribution grid, cost of being designed to accept power-beams from several satellites (as appropriate), etc.

To clarify this, it is assumed that rectennae would be operated by electricity supply companies as one of their facilities, while satellites would be operated by separate microwave power supply companies, as Kassing also discussed [Kassing 2000]. Electricity supply managers operating a rectenna would buy microwave power from the satellite offering the lowest price (assuming satisfaction of agreed microwave-beam specifications), while satellite operators would deliver microwave power to the rectenna operator offering the highest price. As a result, satellites might supply power to different rectennae following a variety of schedules different from constant base load supply. This relationship between rectenna and satellite operators can be expressed simply by the following equation (in units of cost per unit of electrical energy, such as EUR/kWh_e):

Cost of space-generated electricity = Cost of rectenna + Price of microwave power

$$C_{sp} = C_r + P_{mw}$$

Equation 3-1: Cost of space generated electricity

where C_{sp} is the cost on Earth of electricity generated using a space-based system; C_r is the cost contribution of the rectenna and related equipment; and P_{mw} is the price paid for supplies of microwave energy. For some calculations it can be useful to break the cost of the rectenna down further into capital cost and operating cost, to include an efficiency factor into the microwave power price, and other details; none of these are considered in the present analysis.

Importantly, by equating C_{sp} to the current wholesale price of electricity, and knowing the rectenna cost (calculated from its capital cost and operating load-factor) the maximum price which could be paid for microwave power delivered to the rectenna at any particular load-factor can be calculated. In addition, by knowing the satellite's capital and operating costs it is then possible to calculate the lowest load-factor at which a satellite could operate while supplying this power.

To illustrate the use of Equation 3-1 we first use the calculation from the Fresh Look study that the capital cost of the satellite is 92.5% of the total system cost, and the rectenna 7.5%. Making the further assumption that the combined system is competitive with other base load power suppliers if operated at a load factor of 90%, and considering all costs as fixed costs, we can calculate the range of operating conditions (in terms of load factors on rectenna and satellite) under which the output would have the same cost. The result is shown in Figure 3-10: the rectenna could be economically operated with a load factor as low as 60% if the load factor of the satellite from which it was receiving microwave power was 94%.

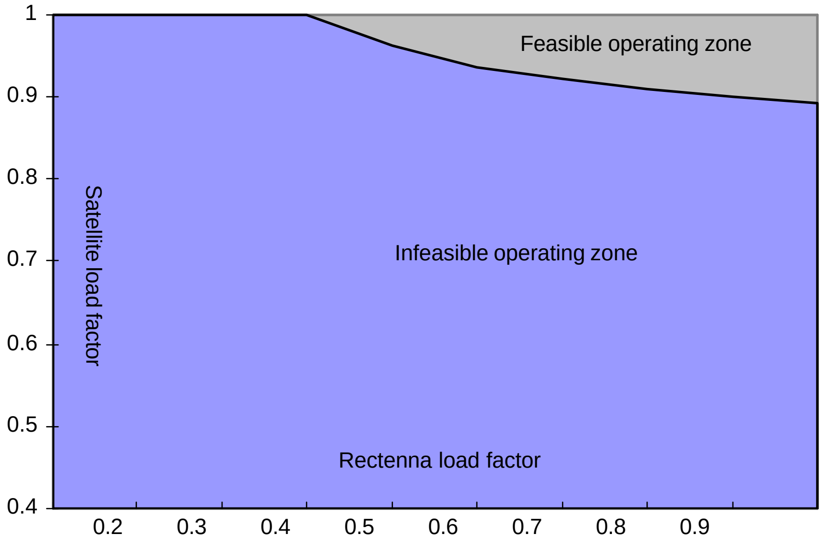


Figure 3-10: Feasible operating conditions of decoupled satellite and rectenna (1)

Wholesale electricity prices differ significantly between countries, regions and over a range of time-scales. Consequently, a system that might be competitive as base load supply only at 95% load factor in one system, could be competitive in another at a lower load factor. Figure 3-11 illustrates the range of feasible operating conditions in the case in which the combined system was competitive with base load power at a load factor of 85%. In this case, the rectenna could be economically operated with a load factor as low as some 40%, if supplied with microwave power from a satellite operating at 94% load factor.

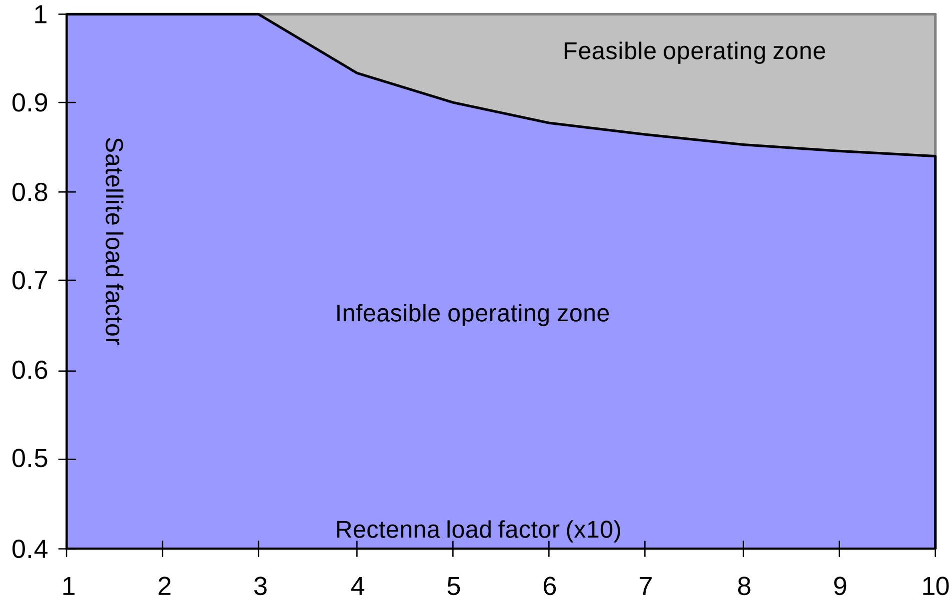


Figure 3-11: Feasible operating conditions of decoupled satellite and rectenna (2)

The above examples understate the system's flexibility because the wholesale price of non-base load power is higher than base load. The extent to which this operational flexibility of space-based solar power supply systems would be used in practice would depend on the difference in the market price of base load power and non-base load power, among other factors. This price difference varies between countries, and under different operating conditions, such as seasonally, whereby the average level of daily electricity output changes over a period of several months. The potential benefits of operating in this way can be estimated by using relevant price data. As a simple example we assume that the price of non-base load power is 33% higher than that of base load power. In this case the range of feasible operating conditions is considerably wider than in the previous cases, as shown in Figure 3-12 for the case in which the joint satellite/rectenna was competitive only at 95% joint load-factor.

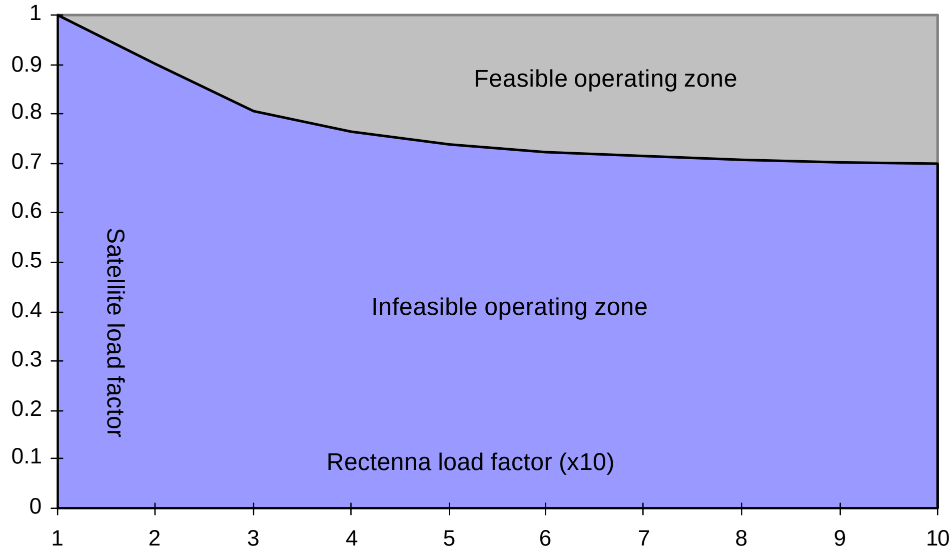


Figure 3-12: Feasible operating conditions of decoupled satellite and rectenna (3)

Clearly, a rectenna that could be operated economically at a load factor of 20% while receiving power from a satellite operated at a load factor of 90% would be a very flexible facility.

These and other potential benefits of operating rectennae and satellites in a "decoupled" way are not discussed or analyzed in the Fresh Look study nor in the 1970s SPS Reference System study. However, as shown above, the additional economic value of being able to operate rectennae at lower load factors suggests that this mode of operation would be used increasingly as the number of rectennae and satellites increased. This is because, as the number of alternative supply sources for each rectenna, and the number of alternative customers for each satellite increased, the overall system's flexibility would improve. This mode of operation might even become the main way of operating solar power satellites and rectennae, linked through a wholesale market for microwave power from space (discussed further in Section 8.3.3b) below).

a) European rectenna conditions

In the Fresh Look study report, the rectenna cost for the 1970s Reference System is quoted as being 21% of the total system cost, while that in the Fresh Look study is some 7.5%; this difference is mainly due to the different frequency assumed for microwave power transmission: at 5.8 GHz the area of a 5 GW rectenna is estimated at some 20 sqkm, compared to 85 km^2 for the 1970s Reference System [NASA 1997, table 6-4, p 118]. This difference has a major impact on the cost of a rectenna, and hence on its operation. Consequently the selection of 2.45 GHz, 5.8 GHz or other microwave frequency is a decision of great significance for the system's economic evaluation.

In Table 5-6 the area of a rectenna for European use is stated as 50.44 km². Using this with the Fresh Look study's cost of \$45.3/m² (48 EUR_{2000}) for the rectenna [NASA 1997, table 6-4, p 118] gives a rectenna cost of \$3,035 (3,217 EUR_{2000}) which is 13.3% of the adjusted total system cost of \$22,845 (24,216 EUR_{2000}). Using this figure of 13.3% as the basis for the same calculations as performed above, Figure 3-13 to Figure 3-15 illustrate the potential for flexible operation of a European rectenna; although scope for flexible operation is reduced due to the higher cost, it would still be substantial.

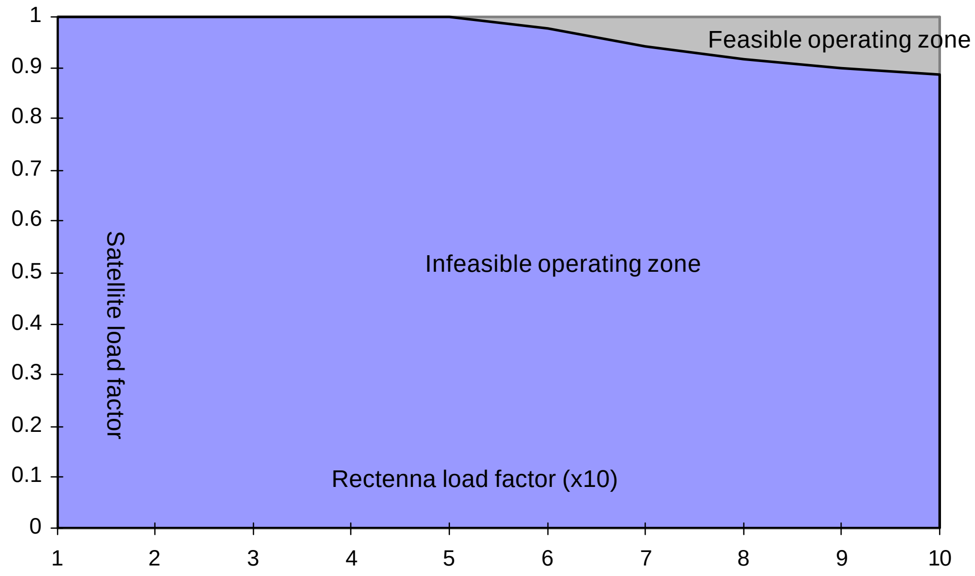


Figure 3-13: Feasible operating conditions of satellite and European rectenna (1)

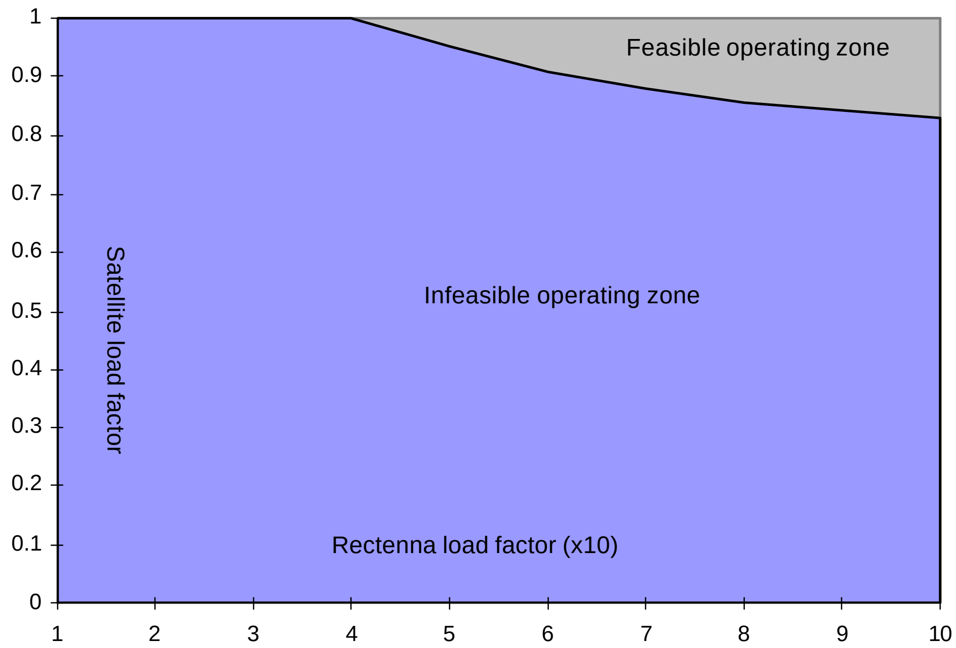


Figure 3-14: Feasible operating conditions of satellite and European rectenna (2)

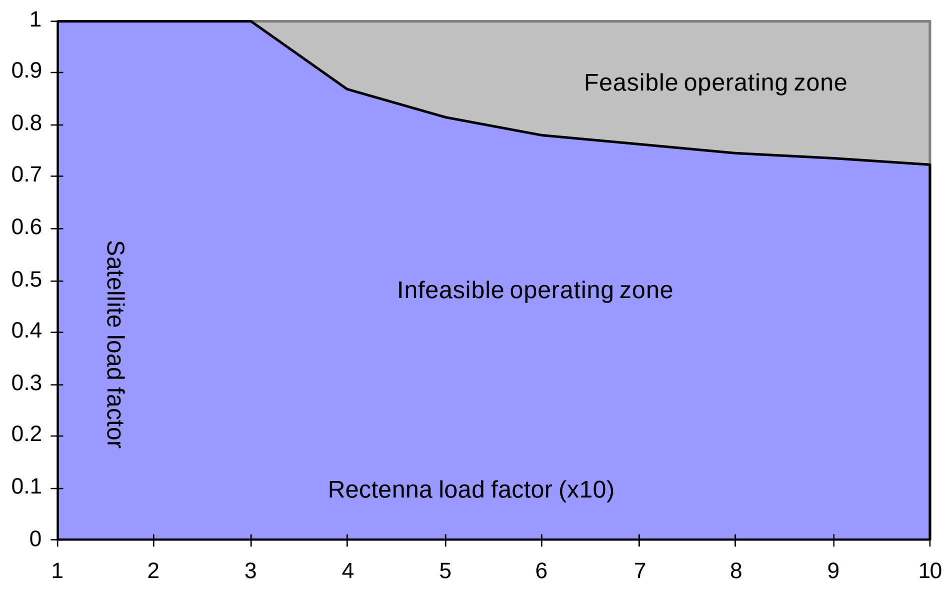


Figure 3-15: Feasible operating conditions of satellite and European rectenna (3)

3.3.2 Shifting power delivery between multiple rectennae

In the "standard configuration" from the Fresh Look study, one satellite would deliver two microwave power beams to two different rectennae with output of 5 GW, from two microwave antennae. The operational flexibility of such a satellite could be increased by designing the satellite to be able to vary the power delivered to each rectenna between zero and more than 5 GW. In the standard configuration, power supply to each of the rectennae could be increased by shifting both beams to deliver to the same rectenna, but only after power delivery to the other rectenna was reduced to zero. However, if the transmitting antennae were designed to have more than 5 GW output capacity, they could operate more flexibly, at some increase in the cost of the satellite. NB a major difference between the 1970s DoE Reference System and the Fresh Look study is the mass and cost of the microwave power transmitting antenna. This was some 15% of the satellite cost in the DoE study [DOE 1980], and 60% in the Fresh Look study [NASA 1997]; such a large difference has major implications for space-based power systems' economics and for the feasibility of flexible operations; it is discussed further in Section 3.4.3.

Boeing, BAe and NASA JSC (Arndt) worked on multiple beams from a single antenna in the late 70'ies – early 80'ies. This concept would allow smaller rectennae to be sited closer to populated areas and power switched between them.

a) Multiple satellites : One rectenna

Another flexible mode of operation would be for two or more satellites to deliver power simultaneously to a single rectenna. This would have the advantage of reducing the rectenna costs/kW of capacity and reducing the land area requirements by 50%. In Section 4.3.2 it is stated that generating 10 GW at a single facility could be accommodated in the European grid forecast for 2030. If the satellites were separated by 3 degrees or more of longitude their microwave power beams would not overlap in the ionosphere, thereby keeping the power density within the ionosphere below any required limit [Gelsthorpe 1980]. (See discussion of ionospheric conditions in Section 3.2.)

Such a double-capacity rectenna would cost more than a single-capacity rectenna, but less than twice as much. In order to estimate the cost of a double-capacity rectenna, the cost-breakdown of a rectenna published in NASA TM58231 [Harron 1981] is shown in Table 3-3. (NB this data refers to the 1970s Reference System; a similarly detailed breakdown of rectenna costs is not included in the Fresh Look study.)

US DoE Reference system	million US$$_{1979}$	million EUR$_{2000}$	
Land cost per m²	105	167	(85 km² @ 1.23 $/m²)
Primary structure	304	486	
RF-DC conversion	661	1058	(Diodes $298m, steel $349m,
DC distribution	268	429	integration $14m)
Control system	61	98	
Utility interface	674	1078	
Total	2073	3316	

Table 3-3: Breakdown of rectenna cost

Table 3-4 shows an estimate of the cost of a double-capacity rectenna based on this data, making the following assumptions: the cost of Land, Primary Structure, RF-DC Conversion and Control System would be the same as for a single rectenna, and the costs of DC Distribution and Utility Interface would be 2/3 higher than for a single rectenna.

Double-capacity rectenna	million US$$_{1979}$	million EUR$_{2000}$	
Land cost per m²	105	167	(85 km² @ 1.23 $/m²)
Primary structure	304	486	
RF-DC conversion	661	1058	(Diodes $298m, steel $349m,
DC distribution	447	715	integration $14m)
Control system	61	98	
Utility interface	1123	1797	
Total	2701	4321	

Table 3-4: Cost estimate of double-capacity rectenna

Based on these cost estimates, the overall cost of a double-capacity rectenna would therefore be some 30% higher than a single-capacity rectenna, and so the cost per kW of capacity of such a rectenna would be only some 65% of a single rectenna; this would significantly increase the potential for flexible operation of the rectenna. The land cost in the Fresh Look study (and the Reference System study) is $1.3/m² (EUR$_{2000}$ 1.38/m²). To the extent that this understates the cost of land for rectennae in Europe, the cost advantage of a double-capacity rectenna would increase. (In Section 4.5) it is stated that the cost of land is not included in the present limited study; however, for long-distance power transmission cables it is taken as 10 EUR/m². Using this figure instead of the $1.3/m²

(EUR$_{2000}$ 1.38/m^2) in the Fresh Look study would add nearly 700 million Euro, or some 20% to the rectenna cost estimated above.)

As another illustration, the cost of a polder to site a rectenna off the Dutch coast in the North Sea, plus cables linking it to the shore, was estimated in an earlier ESA study as some 11 billion Dfl in 1980, or approximately 7 billion Euro (in 2000 Euro) [Bresters 1980]. The same report estimated that this would add some 0.042 Dfl/kWh to the cost of electricity generated by the rectenna, which (using the same conversion factor) gives 0.03 EUR/kWh in 2000 Euro. Doubling the capacity of a rectenna at such a site by delivering two microwave beams would reduce the additional cost of the rectenna proportionately, ie to some 0.02 EUR/kWh. Tripling the output would reduce it even further. Such an offshore site covering tens of square kilometers could be linked by cables to the Netherlands, Belgium, France, Britain, Germany and other countries, thereby facilitating the integration of even 15 GW. Development of such an "energy island" would be one type of "industrial island", as discussed in the civil engineering literature.

3.3.3 De-coupled rectenna and satellite operating schedules

Based on the above considerations, several different flexible modes of satellite operation are possible, in which the delivery of microwave power to rectennae would alter over different time-scales. Each of these modes of operation would be possible using a "standard configuration" solar power satellite, but the flexibility and efficiency could be improved with more advanced designs of power transmitting antenna, as discussed above. The overall system flexibility would increase as the total number of satellites and rectennae increased, leading to "network synergies" as discussed in Section 8.2 and 8.3.3b).

a) Daytime power supply

Daytime demand is typically about 50% higher than base load demand, and lasts for 16 - 18 hours. If a satellite and rectenna pair was used to supply this power at a combined load-factor of say 67%, then the cost of the power supplied would be 50% higher than the cost of base load supply. However, a rectenna used to supply the same power could be economical if the load-factor on the satellite from which it was receiving power was sufficiently high (through supplying power to one or more other rectennae).

b) Medium-term demand/supply shifts

Weather patterns lasting a few days or longer shift actual electricity demand significantly above and below seasonal average figures, as well as altering terrestrial solar power (and wind power) supply. For many regions, short-term weather forecasts up to one week ahead are nowadays sufficiently reliable to enable electricity companies and satellite operators to plan their near-term operating schedules in this way. Electricity companies could therefore make contracts with solar power satellite operators for required supplies above base load or above planned supply. This process could be facilitated by the development of a market for future microwave power supplies similar to the future markets that operate for a range of standard products today; satellite operators would combine a series of such contracts to maximize their revenues.

c) Load-following

Space-based power systems' technical capability to deliver power to a given rectenna on demand and/or at short notice creates the possibility of varying output in real-time in response to changing demand, or of offsetting the natural variation in output of terrestrial solar power facilities. The most efficient means of achieving this would be for a satellite which was load-following on one rectenna to simultaneously adjust its output at another rectenna so as to maintain a high satellite load factor. The price of microwave power delivered in such a relation to a second "passive" rectenna might be discounted appropriately, similarly to the pricing of contracts today for electric power supplies with different interruptibility conditions. The existence of large-scale power storage systems, and/or large-scale use of hydrogen as fuel could make such patterns of power supply more attractive, by providing continuous demand for power.

d) Seasonal changes in electricity demand

The timing of the seasonal peak in demand for electricity varies from country to country, some having a winter peak, and others having a summer peak. A simple means of exploiting this would be to switch the direction of power delivery from a satellite operated at maximum load factor between two rectennae each operated at near to 50% load factors. Such a mode of operation could be used to switch power seasonally between rectennae sited in northern Europe where demand for electricity peaked in winter, and rectennae in the south where demand peaked in summer. Within Europe today, only Greece shows a significant peak in electricity demand in summer; consequently in order to exploit this potential power would need to be supplied to countries outside Europe, as discussed in Section 8.3.3a). The forecast of European electricity demand in 2030 shows a maximum demand of 570 GW in winter, but only 430 GW in summer: so there could in principle be as much as 140 GW available for international sharing in this way.

3.4 Space-based contribution to solar power scenario

In order to ensure the continuation of global sustainable development, there will be a need for some 10,000 GW of CO_2-free electricity generating capacity by 2050 according to

[Hoffert 2002][4]. It is therefore necessary to consider how far progress could be made towards the goal of 500 GW capacity by 2030, and what capacity might be achievable by 2050. Achieving maximum space-based solar energy supply by 2030 would require activities which are on the critical path to start as soon as possible. The three most critical activities are discussed in turn.

3.4.1 Development of low-cost launch system

The Fresh Look study estimates a 7-year development period for a fully reusable launch system capable of costs of $121/kg at a traffic rate of some 130,000 tons/year to LEO, followed by 5 years for production of a fleet of 42 vehicles [NASA 1997] although the system is not described in detail. There are very few studies of launch systems designed to achieve such high traffic-rates; two other comparable studies are briefly described. In a study performed from 1993 through 2002 by members of the Japanese Rocket Society, the SSTO, VTOL launch vehicle "Kankoh-maru" was estimated to be capable of carrying 5 ton payloads to 200 km LEO at a cost of approximately $1.3 million per flight, or some $270/kg. The study (which produced some 100 publications in both Japanese and English) estimated the development and test-flight programme to take 10 years, followed by production of 48 vehicles over a further 7 years, leading to a traffic level of some 70,000 tons/year [Isozaki et al, 1998]. A third pre-feasibility study of a high traffic-rate reusable launch vehicle system was reported in ESA Contract N10411/93/F/TB; this concluded that at a traffic volume as high as 200,000 tonnes/year, a TSTO, HTOL vehicle could reach a launch cost to LEO below $100/kg; development of such a mature launch system was estimated to take some 17 years [Ashford, 1994]. These results are shown in Table 3-5.

4 Though [Hoffert 2002] also admits that 10-30 TW could be produced worldwide by terrestrial PV and wind installations in combination with hydrogen and a global electricity web.

Study	Japanese Rocket Society	Bristol Spaceplanes	"Fresh Look" Study
Study date	1993-2002	1993-1994	1995-1997
Development time	10 years	17 years	7 years
Vehicles built	52	50	42
Vehicle payload	5 tons	10 tons	11 tons
Traffic T/year	70,000	200,000	130,000
Launch cost $/kg	270	<100	121
Reference	[Isozaki 1998]	[Ashford 1994]	[NASA 1997]

Table 3-5: Studies of high traffic rate launch systems

Although the estimates of 7, 10 and 17 years for development differ significantly, the three systems' specifications are different, and the three studies' estimates of cost/kg relative to annual traffic rate are consistent. While the idea that launch costs could fall 99% may seem unlikely prima facie, it is important to recognise that they have not fallen at all since the first satellite launch 47 years ago. The "Soyuz" launch system remains the lowest-cost. This situation is unique in the history of transportation systems (at least through the 19th and 20th centuries), and suggests that there is potential for substantial cost reduction.

Furthermore, the estimate in Section 9 of the effect of learning and scale economies in the mass-production and operation of expendable launch vehicles for the case of high traffic rates shows some of this potential. At such high traffic rates even expendable launch vehicles would achieve major cost reductions; consequently, reusability need reduce costs only by a further factor of 2 - 3 in order to meet the targets in Table 3-5. It might therefore be realistic to assume that a reusable vehicle system suitable for launch of space-based solar power plants could be developed in 15 years. In this case, cargo launch operations could start in the 2015 - 2020 timeframe, which is a more conservative estimate than the Fresh Look study. This would be a key milestone on the critical path towards space-based solar power.

3.4.2 Development of space-based solar power pilot plant

An essential step in the development of a new electricity generation system is the production and operation of one or more demonstrator systems, or a "pilot plant", prior to investment in a full-scale commercial system. On this issue the Fresh Look study states:

"The driving assumption is that the non-recurring costs for all of the SPS concepts would be based on flight testing a 10 MW demo version of the particular concept in LEO" ([NASA 1997], p 109).

Starting before the Fresh Look study [NASA 1997], a large part of the research work performed on space-based solar power in Japan since 1990 has concerned the planning of a 10MW pilot plant system to be operated in low equatorial orbit. A 1991 paper describing the main features of the proposed system won the $3,000 "SPS 91 Prize" for the best proposal at the SPS 91 Conference in Paris [Nagatomo et al, 1991], and work has continued since then on many different aspects of the project [Nagatomo et al, 1994]. Indeed, work on this pilot plant system design , which was later named "SPS 2000", represents by far the largest coordinated body of work in Japan focussed on space-based solar power; it has produced 400 publications in several languages; and it has involved field visits to most of the countries on the equator to establish an international network of collaborating researchers and government staff. A partial list of publications includes 300 reports and papers through 1999 [Sasaki, 2001], and work has continued over a wide range of fields since then. Its potential importance has recently been emphasised by a team of outstanding American researchers [Hoffert 2002], and an invited paper on the project is to be included in a special issue of "Energy" journal [Collins 2004].

Led by the Space Power Engineering Section at ISAS in Japan, this work has been based on the idea that only the demonstration of an operational SPS system supplying 10 Megawatts of electric power to real customers could convince the electricity industry that space-based solar power supply is feasible, reliable and could be an attractive investment. The system must be designed for minimum cost (the target is the cost of a terrestrial photovoltaic plant with similar output), and be able to be upgraded progressively. The satellite should be in LEO, since an antenna needed to send even a weak microwave power beam from GEO to a rectenna on the Earth's surface would too expensive for a demonstrator project. Only equatorial orbits offer the advantage of being able to deliver power to customers on every orbital pass (ie every 100 minutes, unlike inclined orbits). The system is designed to use existing launch systems, and to deploy automatically in orbit.

Work towards fulfilling this last requirement has clarified the major risk factor for a 10 MW LEO pilot plant. With a mass of some 200 tons, self-deployment would require the payloads from several successive launches to perform automatic rendezvous and docking, followed by automatic deployment to dimensions of some 300 metres in length and breadth. Most of this process cannot be tested realistically on Earth, and so, using existing technology, there is a high risk of a failure that could prevent the completion of the system. Although collaboration with both Russia and USA has been discussed, neither of these countries has the capability to launch crews to equatorial orbit. The alternative of launching the pilot plant satellite into an inclined orbit and subsequently shifting its orbital plane to equatorial has also been discussed, but this would add greatly to the satellite's complexity and cost.

a) Potential key role of Kourou-Soyuz launch facility

In this context, ESA's 2003 decision to build a Soyuz launch facility at Kourou will create a new capability that could definitively resolve this outstanding problem. The ability to send trouble-shooting crews into equatorial orbit, using the most reliable, low-cost launch vehicle, would give Europe the opportunity to play a key role in realising a space-based solar power pilot plant.

That is, building and operating a pilot plant are on the critical path to establishing a commercial space-based solar power supply system; this energy option will not exist until a pilot plant is in operation. The "SPS 2000" study aimed to achieve this through international cooperation at the earliest possible date. However, this project's prospects are effectively frozen at present for lack of any back-up in the event of problems during deployment; as of early 2004 the Japanese government has no plans to develop an independent capability to launch crews to equatorial orbit. (For completeness, it should be noted that in early 2004 the Japanese government announced a review of space policy which will specifically include reconsideration of its policy towards crewed space activities.) The timetable over which the Kourou-Soyuz project is realised is therefore also on the critical path of a scenario to develop space-based solar power supply systems, through enabling the realisation of a 10 MW low equatorial orbit pilot plant. The first Soyuz launch is provisionally planned for 2006; crewed launch capability could therefore become available a few years later.

3.4.3 Microwave power transmission system (MPTS) R&D

A critical field for research is the microwave power transmission and reception technology to be used by space-based solar power systems. This directly affects the size of rectennae which influences both their ease of siting and their cost, and hence the flexibility with which they could be operated. The design of the microwave power transmission system therefore greatly affects the overall economics of space-based solar power. This subject is particularly important for Europe, since the cost and availability of land are different from the USA, which would lead to a different optimum system design.

This is because the diameters of the transmitting and receiving antennae are inversely related; thus, for example, using a transmitting antenna with twice the diameter would permit halving the rectenna diameter (subject to atmospheric power-density constraints).

The optimum system configuration is the result of a trade-off between rectenna cost and satellite antenna cost; consequently for relatively high-cost rectennae, such as in Europe, the optimum satellite antenna size will be larger than for a satellite optimised for low US land cost. In addition, oversized power transmitting antennae could be used to transmit multiple microwave beams to different rectennae of correspondingly smaller size, for which it would be easier to find sites (as proposed also for a lunar power system). In this context, the reasons why the microwave power transmitting antenna in the 1979 Reference System was only some 15% of the cost of the satellite [Harron et al, 1981], but some 60% in the Fresh Look study [NASA 1997] need to be clarified, and a satellite design appropriate for Europe produced, making use of Europe's considerable expertise in antenna technology.

Alternatively, Boeing and NASA JSC (Arndt) identified beam shaping via steered phased arrays and adaptive optics as an option to reduce rectennae land requirements.

3.4.4 Critical path to space-based solar power supply

Table 3-6 illustrates the fastest path that might be realistically possible towards space-based solar power supply systems. It is not a recommendation, but an illustration of the fastest rate at which space-based solar power supply capacity might start to be developed, and the preceding activities on which this would depend. Provided that the three critical activities of reusable launch vehicle development, pilot plant development (which would depend on Soyuz operations from Kourou), and MPTS R&D were started soon, commercial SPS production could apparently begin in about 2020 at the earliest.

	2005	2010	2015	2020	2025
Kourou Soyuz launch facility	Construction	Crewed Operations			
Equatorial orbit pilot plant	Planning	Deployment	Operation		
Reusable launch vehicle	Development		Testing	Operations	
Space solar power supply	Preparatory R&D		Planning	Production @ 10GW / year	

Table 3-6: Critical path scenario to space-based solar power supply

At the production rate of 10 GW/year described in the Fresh Look study, this would lead to space-based solar power capacity of a maximum of 100 GW in 2030. Thereafter, if capacity grew at a constant rate of 10 GW/year it would reach 300 GW by 2050. However, related technological capabilities would be likely to progress from 2030. Technology in competing fields will also advance, so that the relative competitiveness of space-based systems can not be predicted; however, if the energy payback-time shortens, this would enable the rate of capacity growth to accelerate, leading to a greater contribution to world low-CO_2 electricity supply during the middle of the century, if this was considered necessary, as estimated in [Hoffert 2002].

4 POTENTIALS AND SYSTEMS ASPECTS

In the course of this chapter, system issues are described and – where required – defined.

4.1 Geographical scope

As geographical scope of this study, we define an enlarged Europe of some 30 countries in the year 2030.

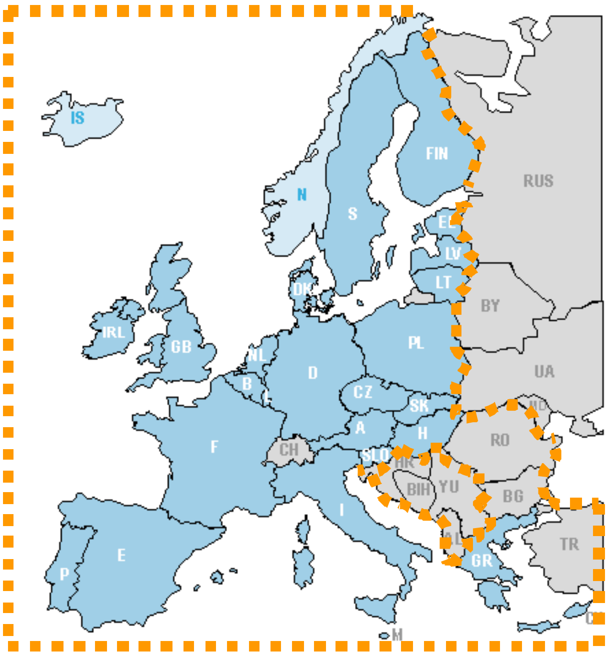


Figure 4-1: Geographical scope (HyNet modified by LBST)

For the upcoming decades we expect that the political integration process in Europe will continue at the pace which is currently in political discussion.

On the European power system level, this process is ahead of the political integration (see chapter 4.3).

4.2 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 according to Figure 4-2.

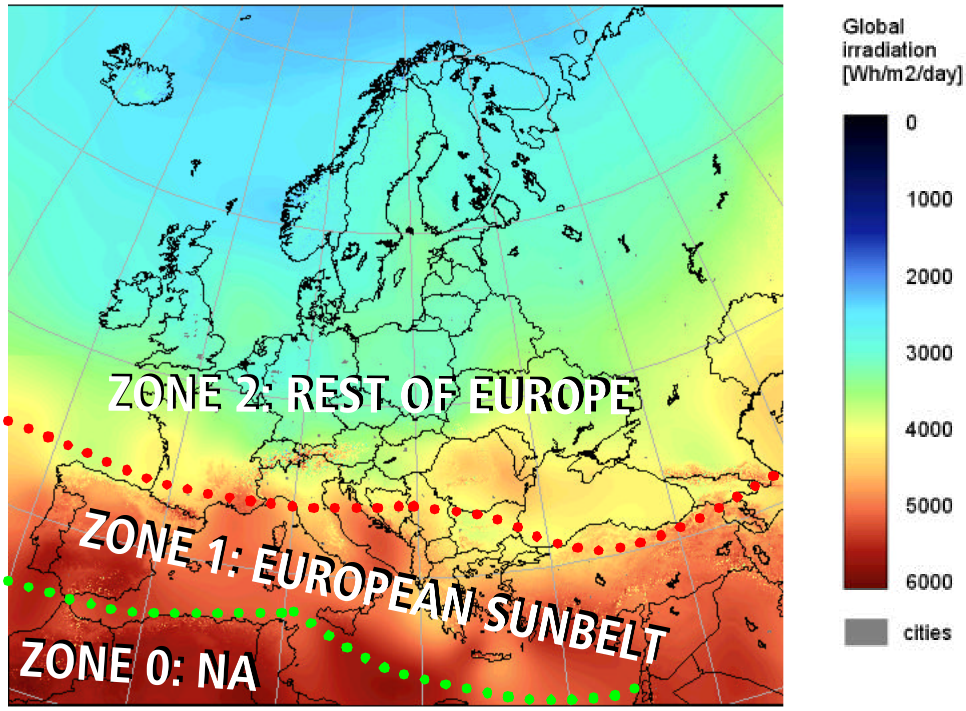


Figure 4-2: Geographical distribution of solar irradiation and definition of 'sun zones' (PV-GIS modified by LBST)

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.

Details on the derivation of solar potentials for terrestrial solar power systems are given in the Report Annex A1.

4.3 European grid

The European grid comprises the associations of transmission system operators (TSO) depicted in Figure 4-3.

Figure 4-3: Associations of transmission system operators in Europe [CENTREL 2003]

Since 1997, a power line a connects the North African (Morocco) and the European grid. Its net transfer capacity (NTC) is 400 MW_e. The net transfer capacity shall be doubled by the year 2006 [EuropaSur 2003].

Since January 2003, Bulgaria and Romania are members of the UCTE. Depending on the availability of data, either the Former Yugoslavian Republic or Bulgaria/Romania are taken into consideration. The resulting error is significantly below the uncertainties of any of the other data extrapolations.

In the framework of the scenarios developed in this study, we assume that the European grid will strongly be enforced for at least two reasons:

- Increasing market demand for electricity exchange due to the liberalization of the European energy markets
- Increasing electricity exchange due to the integration of renewable energies in the European electricity grid (close future: wind; mid-/long-terme: solar)

4.3.1 Siting assumptions

In the aftermath of the September 11th attack and in the eve of a decline of fossil energy supply, energy security has become a major issues in Europe. Installations sited in Europe have a strategic advantage compared to installations in North Africa. Long-distance energy transmission from North Africa to the European continent poses an additional cost and risk burden. The implication of the PV module price on the electricity generation costs are anyway significantly higher than its sensitivity towards solar irradiation. The two sensitivities are depicted in Figure 4-4 according to [Kurokawa 2003].

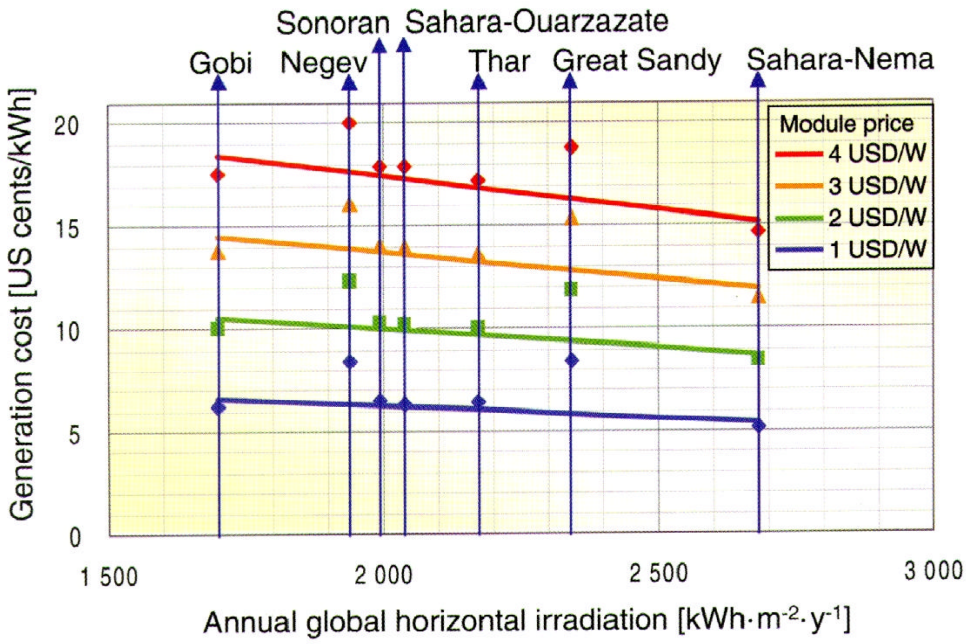


Figure 4-4: Best estimates of PV electricity generation depending on the module cost and solar irradiation [Kurokawa 2003]

Consequently, we decided to favor the siting of power plant installations within the European borders as far as possible. Only in the case where scenario demand exceeds the European generation potentials, energy generation and transmission facilities are placed outside Europe.

In case of terrestrial solar applications, the focus on the European sunbelt results in lower overall irradiation values which consequently leads to lower specific yields of electricity. On the other hand, the effort for power transmission is lower compared to North African sites.

As solar thermal power plants require as much direct sunlight as possible, their siting on the European continent is restricted to the European sunbelt (see definition of sun zones in Figure 4-2 in chapter 4.2). Analogue to PV, SOT plants are preferably sited in the EU sunbelt. North Africa is only taken into account in the 500 GW scenario, where some 40% of all installations are placed. However, the lower annual irradiation is compensated by avoiding long-distance HVDC transmission lines. These would result in larger investment amounts, higher operational costs and power transmission losses. Cost results in chapter 5.1.3 affirm this approach. Furthermore, the security of energy supply is thus given a high priority.

In the aftermath of the terrorist attack on the World Trade Center on September 11th, 2002 in New York, the susceptibility of critical facilities to a single incident has become another issue. We therefore favor a siting strategy which is as geographically distributed as possible. In case of terrestrial solar applications, this would mean that solar power systems are equally distributed between Portugal and Turkey. For PV siting, roof, facades and sound absorbing walls are primarily applied to avoid competition with possibly competing use of space.

Regarding the siting of terrestrial facilities of space-based solar power systems, rectennae must also be sited in zone 2 'rest of europe', in North Africa or off-shore.

For base load and non-base load scenarios, additional rectennae areas are selected in zone 2 and not in North Africa due to additionally requried power transmission via HVDC from North Africa and the more expensive off-shore rectenna technology respectively.

For the 500 GW base load scenario, 80 rectennae are sited along the 40° latitude in zone 1 'European sunbelt', 15 rectennae along the 45° latitude and 5 rectennae are installed along the 50° latitude throughout central Europe.

4.3.2 Grid limitations

At a maximum load of 220 GW electricity supply failure of maximum 5,000 MW can be compensated [VDI 1994]. This means that one single power station or one single grid connection point should not exceed 5 GW. In this study a base load of 500 GW is assumed. Therefore 10 GW 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 high risky for the stability of the electricity grid and the security of electricity supply.

4.3.3 Power transmission

In the framework of this study, only long-distance energy transmission is assessed. The requirements of energy transmission generally apply to both terrestrial and space based power generation. Decentralized power generation from terrestrial PV systems may solely rely on the low voltage grid (400 V 3-phase).

We assume, that the European high voltage grid will be continuously reinforced 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, will also require a powerful European backbone electricity grid. Discussions regarding the future reinforcement as well as geographical expansion of the European high voltage grid are underway at various parties [DENA 2004] [UCTE 2004] [UCTE 2004a] [Euro-Med 2003] [CIGRE 2001].

Subsuming a geographically and technologically broad band of electricity producers and consumers, the European electricity grid can be regarded as a kind of 'virtual electricity storage'.

In general, possible means of long distance energy transmission are:

- High voltage alternating current (HVAC)
- High voltage direct current (HVDC)
- Hydrogen (H_2)

Power transmission technologies are described in further detail in the Report Annex (see chapter A1). Therein, the technology of energy storage via hydrogen is also discussed.

To assure a minimum of comparability, the two consortia were prompted at the first workshop meeting on 11./12. January 2004 at ESTEC to **agree on the certain technical and economical parameters for further scenario calculations.** These parameters are enlisted in Table 4-1:

Component	Parameter	Today (600kV)	2030 (800kV)
Line	Losses	3.3%/1000km	2.5%/1000km
Line	Investment	300,000 EUR/km	300,000 EUR/km
Headstation	Losses	0.7%/station	0.5%/station
Headstation	Investment	700,000 EUR/station	700,000 EUR/station

Table 4-1: Technical and economic parameters for HVDC transmission systems applied for scenario calculation as defined by both consortia

In the course of the study, HVDC is applied to transmit electricity from North Africa to Europe and for large-scale power distribution within Europe. The threshold when to apply HVDC and not HVAC lines for European power distribution is set to 10 GW_e per location. The techno-economic parameters of a 'standard' HVDC line – as they are applied in the course of this study – are depicted in Table 4-2.

Standard HVDC length for power distribution of large-scale power plant installations in Europe e.g. Spain ⇔ Amsterdam/NL, Turkey ⇔ Prague/P	1,500 km
Standard HVDC line length for large-scale power transmissions from North Africa to the European grid e.g. Morocco ⇔ Basel/CH, Tunisia ⇔ Marseille/F	2,500 km

Table 4-2: Standard HVDC line lengths

4.3.4 Power demand

As agreed on the first project workshop, a common power demand profile was assumed. This reflects today's power demand in EU-30 based on UCTE, CENTREL and further country specific data on power demand as well as reflecting a certain growth in energy demand from today to 2030. The synthesis of the EU-30 2030 power demand curve is derived in the subsequent chapters.

a) European power demand 'EUROPE-2030'

The European grid is metaphorically regarded as an electricity lake. Numerous power producers feed the grid to cover a virtual single European 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 (see Figure 4-5 to Figure 4-7).

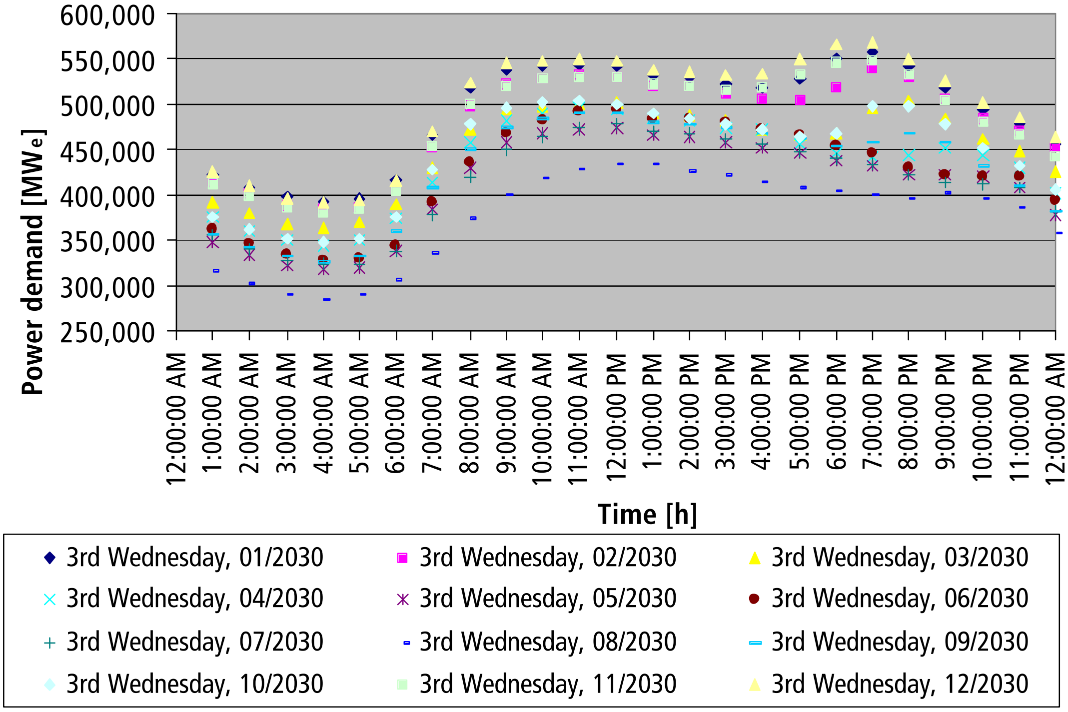


Figure 4-5: Power demand for every third Wednesday in 'EUROPE-2030' (LBST based on UCTE data)

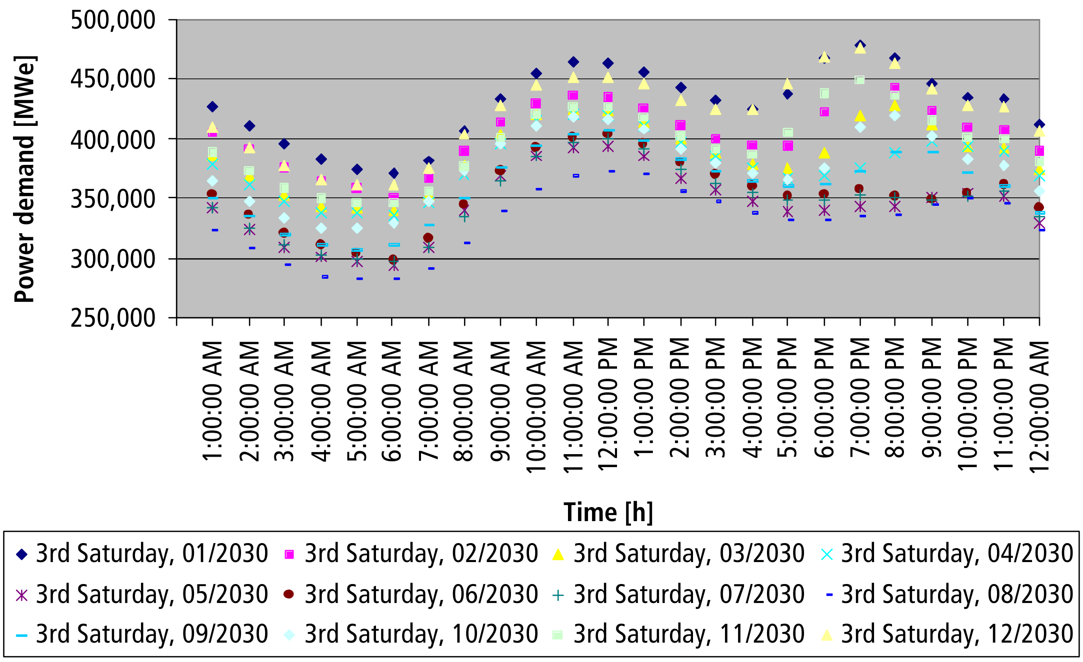


Figure 4-6: Power demand for every third Saturday in 'EUROPE-2030' (LBST based on UCTE data)

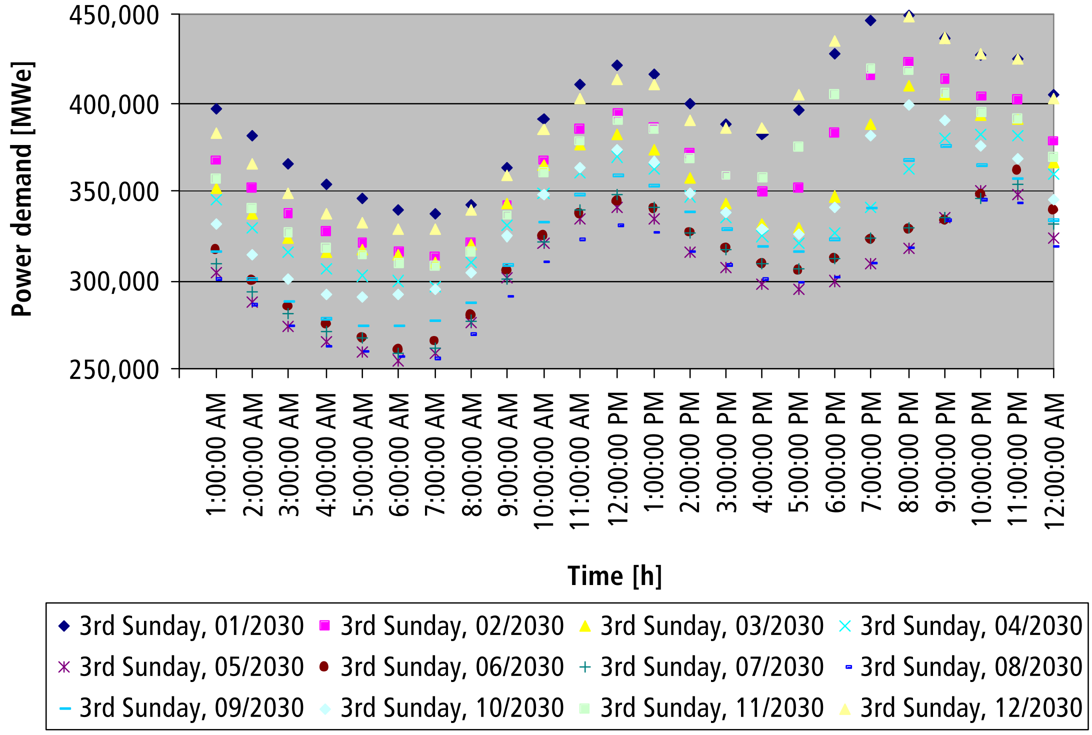


Figure 4-7: Power demand for every third Sunday in 'EUROPE-2030' (LBST based on UCTE data)

These singular data are interpolated to form a load curve which covers a whole year in hourly steps. To adapt this data regarding both geographical and time scope, a mathematical approach was applied which is outlined in Figure 4-8:

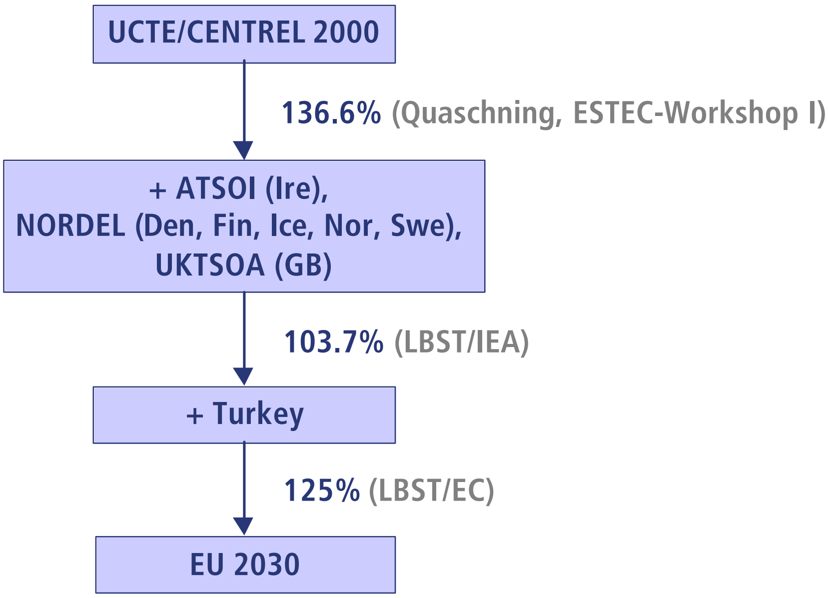


Figure 4-8: Procedure to derive EU power demand in 2030 with up-scaling factors

The up-scaling factor of 103.7% (Turkey) is derived as follows: The consumption of electrical energy in the year 2000 in Turkey is 104,520 GWh_e [IEA 2000]. The consumption of electrical energy in the year 2000 in the EU is 2,851,096 GWh_e [UCTE 2000]. The up-scaling factor is then calculated according to Equation 4-1.

$$F = 1 + \frac{W_{Turkey}}{W_{EUextended}}$$

Equation 4-1: Up-scaling factor 'Turkey'

As a first assumption, the up-scaling factor of 125% (2000 $\rightarrow$ 2030) is in general accordance with the increase in energy demand in EU-30 by 25% between 1998 and 2030 [EC 2001a].

The monthly consumption of electrical energy in the EU-30 in 2030 is stated in Figure 4-9.

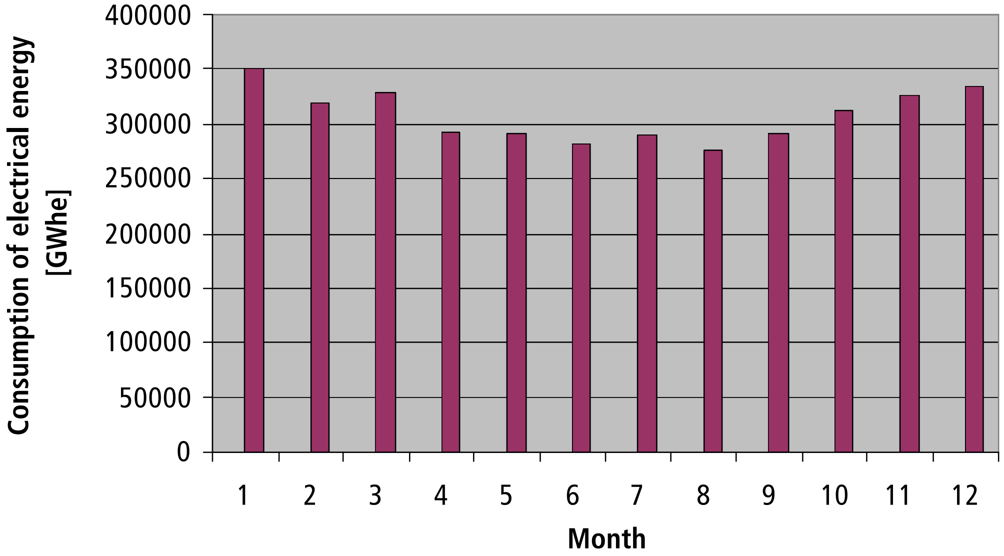


Figure 4-9: Monthly energy consumption based on [UCTE 2003] data and extrapolated to 'EUROPE-2030'

b) Regional power consumption

At some scenario size, the power produced in power plants will exceed the 10 GW_e threshold (see chapter 4.3.2) and thus has to be transmitted via high voltage direct current line (HVDC). Power which is locally consumed is not required to be transmitted via HVDC. This examination is relevant for the calculation of the integration of solar thermal power plants in the EU sunbelt and for the rectenna siting.

To derive the local power consumption, the following approach was selected: As a first assumption, annual power consumption per capita will be approximately equal in Europe in 2030. The local power consumption is then determined by the population.

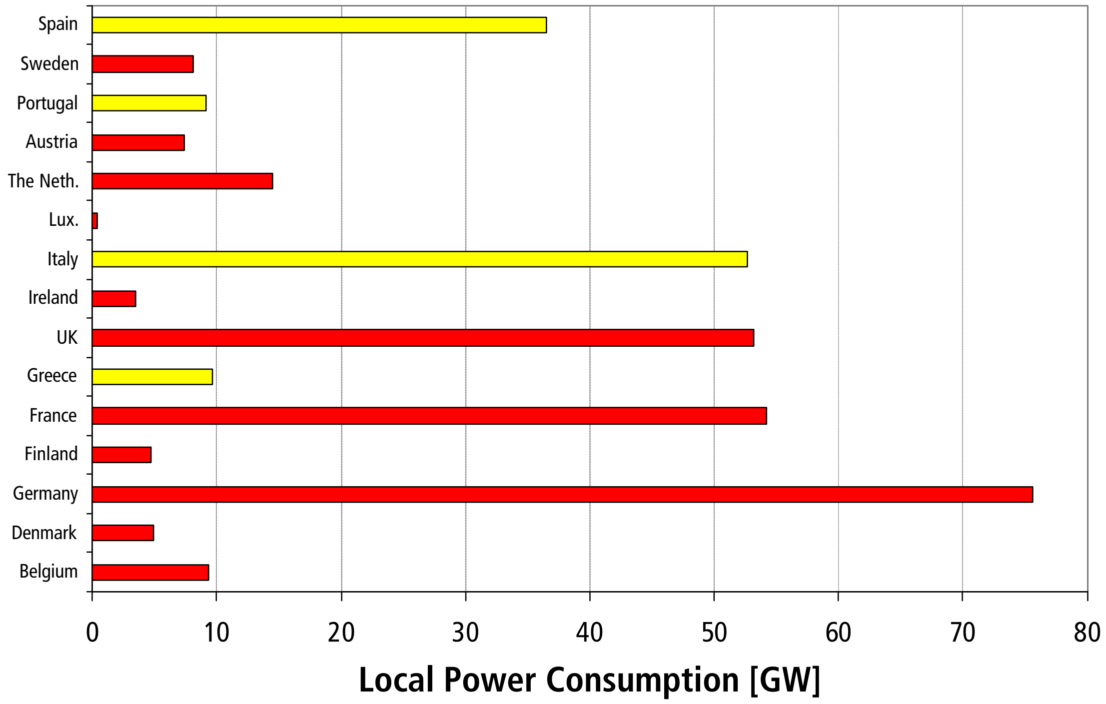


Figure 4-10: Regional power consumption of EU-15 in the framework of 'EUROPE-2030' according to the 500 GW_e scenario (zone 1 – yellow, zone 2 – red)

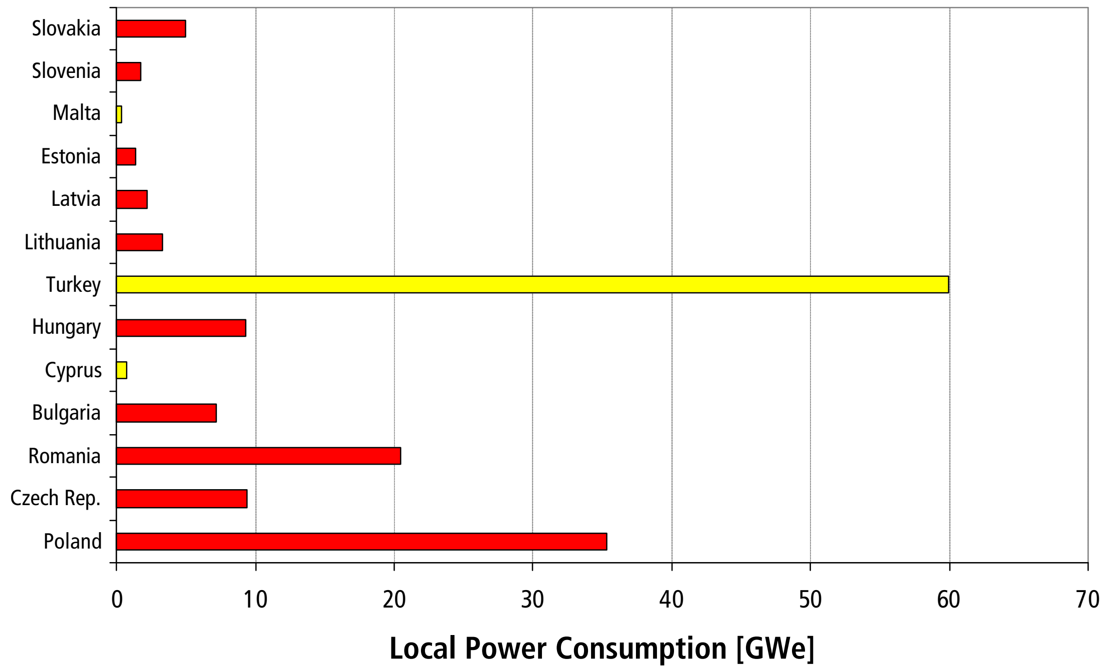


Figure 4-11: Regional power consumption of potential new EU member state in the framework of 'EUROPE-2030' according to the 500 GW_e scenario (zone 1 – yellow, zone 2 – red)

4.4 Energy storage

In this chapter various electricity storage technologies are presented and discussed for their further application within the framework of this study. Relevant means of electricity storage technologies are then selected.

4.4.1 Energy storage systems

The general requirements of electricity storage apply to both terrestrial and space based power generation.

In general, possible means of energy storage are:

- Batteries
- Pumped hydro energy storage (PH / PS)
- Compressed air energy storage (CAES)
- Hydrogen storage

– Flywheel

– Supercapacitor

– Superconducting magnetic energy storage (SMES)

Every single of these energy storage technologies provides specific advantages and disadvantages. Aside costs, these are mainly power and energy parameters.

The operational field of various energy storage technologies is depicted in Figure 4-12.

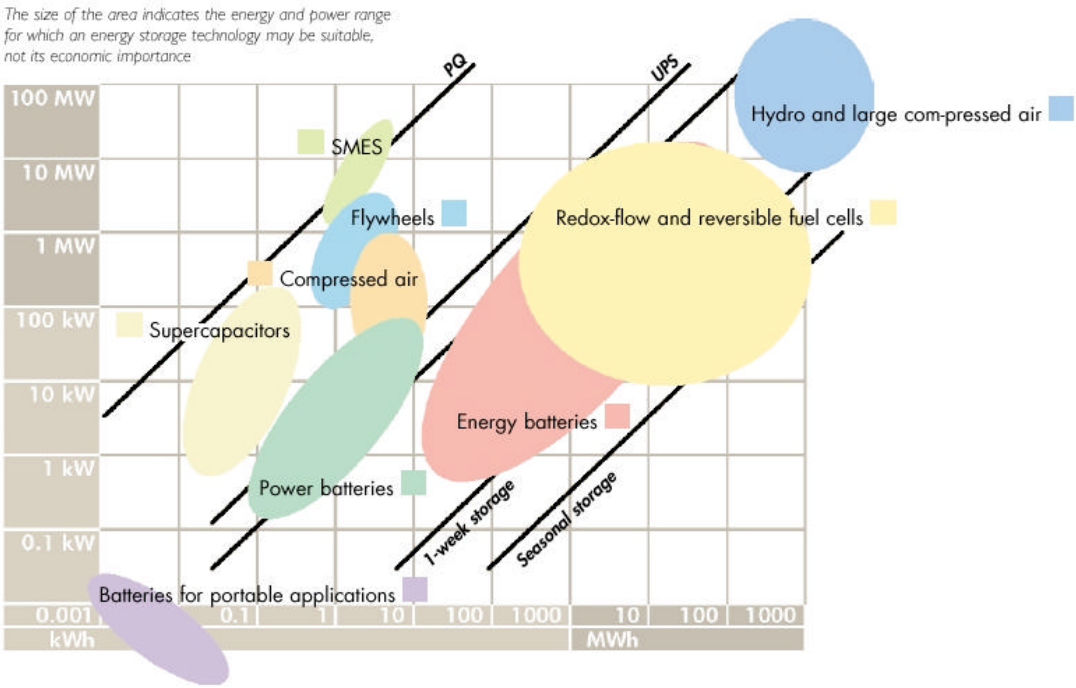


Figure 4-12: Operational field of various storage system technologies [EC 2001]

Costs of various means of energy storage are given in Figure 4-13. The cost of energy storage is sensitive to the period of time the energy is required to be stored (equivalent full load cycles per year).

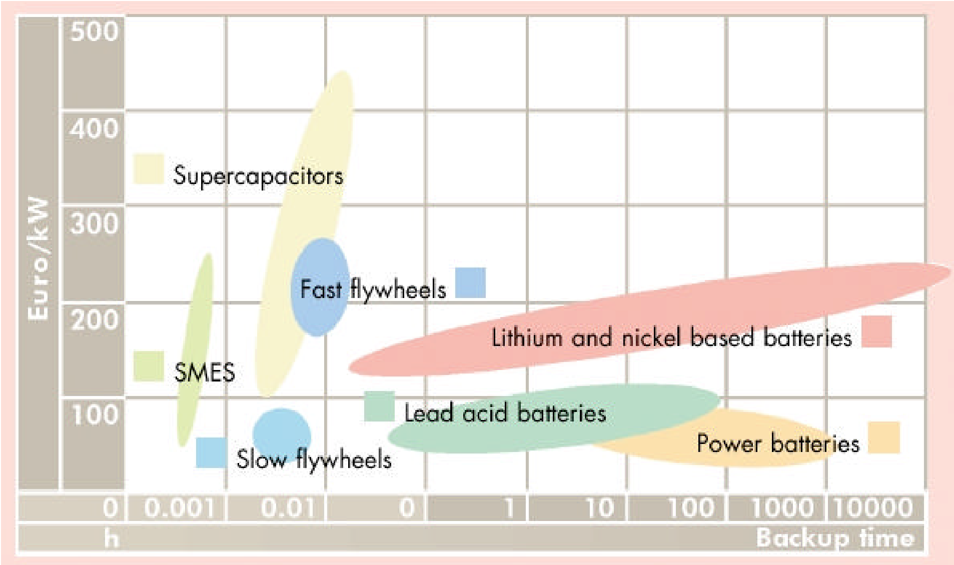


Figure 4-13: Cost of various energy storage system technologies [EC 2001]

The stage of development greatly varies between the above stated means of energy storage. A more detailed discussion on the technical capabilities of the various energy storage technologies is given in the Report Annex (see chapter A1).

4.4.2 Selected concepts

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 the 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 haven a high loading/unloading cycle efficiency and are already in operation for many years.

a) Hydrogen

The efficiency of the electrolyzer is assumed to be 65% related to the lower heating value (LHV) of the delivered hydrogen including all auxiliaries (AC/DC converter, pumps, blowers, control unit). The investment for the electrolysis plant has been assumed to be 1,500 EUR per Nm^3/h or 500 EUR per kW of hydrogen.

Generally for large scale hydrogen storage depleted natural gas fields can be used. But depleted natural gas fields are not available everywhere. In this study it is assumed that the hydrogen is stored in spherical pressure vessels.

The maximum pressure of the spherical pressure vessels is assumed to be 2 MPa. Since the electrolyzer delivers hydrogen at a pressure above 2 MPa no additional compression is required.

The solar thermal power plants are already equipped with a steam turbine. Therefore only the gas turbine part has to be added to get a CCGT. Therefore in this study it has been assumed that the additional investment for the CCGT is 500 EUR per kW of rated electricity output. For the PEMFC the specific investment also has bee assumed to be 500 EUR/kW_e.

Within the framework of this study, the basic assumptions as indicated in Table 4-3 are applied for scenario calculations.

Component	Parameter	Today	2030
Electrolyzer	Efficiency	65% (LHV)	65% (LHV)
	Investment	500 EUR/kW_{H2}€	500 EUR/kW_{H2}€
	O&M	1.5% of investment	1.5% of investment
Spherical pressure vessel	Investment	1.92 million EUR /unit	1.92 million EUR /unit
	Pressure	0.2 to 2.0 MPa	0.2 to 2.0 MPa
	Volume	3,000,000 l	3,000,000 l
	Net storage capacity	49,300 Nm^3 H_2	49,300 Nm^3 H_2
Fuel Cell/CCGT	Efficiency	50% (LHV)	55% (LHV)
	Investment	500 EUR/kW_e	500 EUR/kW_e
	O&M	0.01 EUR/kWh_e	0.01 EUR/kWh_e

Table 4-3: Basic assumptions for hydrogen production, storage and re-electrification

The efficiency of fuel cells including all auxiliaries are approximately equivalent to large combined cycle gas turbine (CCGT) power plants. But fuel cells achieve the efficiency of CCGT power plants (50 to 60%) already at a rated electricity output of above tens of kW_e whereas CCGT power plants reach an efficiency of more than 50% when the rated capacity exceeds 100 MW_e.

b) Pumped hydro storage

One of the largest pumped hydro power station in Europe is located in Goldisthal in Thuringia in Germany. Today the plant mainly is used to store electricity from base load operated brown coal fueled power stations to compensate demand fluctuations. The start up time of the pumped hydro plant for increasing the power output from 0% load to 100% load is 110 seconds.

The plant has four turbines. The maximum total electricity output is 1,060 MW. The higher level basin can store 12 million m^3 the lower level basin can store 18 million m^3. The hydraulic head is indicated with 300 m. The maximum flow rate per turbine is 100 m^3/s which lead to an electricity output of 265 MW per turbine. If all turbines are operated at full load the maximum water flow is 400 m^3/s or 1.44 million m^3/h. As a result the maximum storage capacity is approximately 8.8 GWh_e sufficient for 8 hours of full load operation. The investment of the pumped hydro power plant in Goldisthal is indicated with 620 million EUR [IWR 2/2003], [RegioWeb 2003].

Table 4-4 shows the basic assumptions for pumped hydro used in this study.

Component	Parameter	Today	2030
Pumped hydro power station	Efficiency	75%	85%
	Investment	700 EUR/kW_e	600 EUR/kW_e
		+ 14 EUR/kWh_e	+ 12 EUR/kWh_e
	O&M	0.006 EUR/kWh_e	0.004 EUR/kWh_e

Table 4-4: Basic assumptions for pumped hydro

In this study for 2030 the investment has been assumed to be 600 EUR per kW plus 12 EUR per kWh. If the capacity were assumed to be 1.06 GW and the storage capacity would be assumed to be 8.8 GWh the investment would be about 742 million EUR which is above the 620 million EUR for Goldisthal plant. Therefore the 600 EUR per kW plus 12 EUR per kWh are on the safe side.

In the following the required land has been estimated whereas the Goldisthal plant has been used as reference plant. Table 4-5 shows the technical data of the Goldisthal plant.

Upper basin	12,000,000 m^3
Rated capacity	1060 MW_e
Flow rate	400 m^3/s
Storage capacity	8.33 h
Storage capacity	8,833 MWh_e
Land area upper basin	55 ha
Land area lower basin	78 ha
Total	133 ha
Specific land area	0.15 km^2/GWh_e

Table 4-5: Technical data of the pumped hydro power plant in Goldisthal [FH Erfurt 2002]

Table 4-6 shows the required land for the pumped hydro plants for the different scencarios.

Scenario	**GW_e**	**0.5**	**5**	**10**	**50**	**100**	**500**
Annual electricity output	TWh/yr	4.4	43.8	87.6	438	876	4,380
Thereof via pumped hydro	-	27%	27%	27%	27%	27%	27%
Thereof via pumped hydro	TWh/yr	1.2	11.8	23.6	118	236	1,180
Number of loading/unloading cycles per year		50	50	50	50	50	50
Required land area	km^2	3.6	35.5	71.1	355	711	3,553
Number of Goldisthal plants	-	2.7	26.7	53.4	267	534	2,672

Table 4-6: Land use for pumped hydro for the different SOT scenarios

For comparision: in 1999 about 24.3 TWh has been generated via pumped hydro within the EU 15 [Crampes et al 2003]. If the number of full load loading/unloading cycles were assumed to be 100 (typical for existing pumped hydro) about 28 pumped hydro storage plants would be required. Then the area occupied by existing pumped hydro is about 37 km^2.

4.5 Land use

To determine the cost of the land which is occupied by power production and transmission facilities is a difficult matter (see chapter 4.3.1). A brief discussion on the land use issue is given in chapter 1.4 (Basic definitions and assumptions) and 10.2.5 (Economic risks).

At the first project workshop, it was thus jointly 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**.

4.6 Decommissioning and recycling

This chapter shall give an overview of the decommissioning procedure and major recycling issues concerning terrestrial and space-based solar power systems (SPS). An in-depth analysis of recycling schemes for either system is beyond the scope of this study and remained highly speculative for SPS.

4.6.1 Terrestrial solar power systems

Analogue to development scenarios of [Kurokawa 2003], mass components of large-scale terrestrial solar power systems are manufactured close to the major centres of demand on a mid- to long-term perspective. Consequently, recycling plants would be in geographical proximity to supply / demand, too. In this study, this would imply North African manufacturing and recycling plants only in case of the 500 GW SOT scenario.

a) Photovoltaic (PV) power systems

Historically, the question of how to recycle PV system components continuously rising in the research and development agenda as the power plants of the earliest years are coming into age. Thus, a broad range of scientific publications document the efforts which are currently underway in this field, such as [Zangl 2004], [Springer 2003], [Fthenakis 2002], [Frisson 2000], [WCPEC 1998].

To a large extend, PV power systems will be operated on a highly decentralised basis in Europe (between a couple of kW_p and several hundred kW_p, up to some MW_p). These systems will be mostly owned and operated by individuals and private operating consortia. Thus, recollection schemes comparable to other home electric/electronic products may be applied. This may be for example the recollection by the installer of the new systems as it is already well established today with residential heating systems.

Decommissioned system components may then be transport to central, brand independent recycling stations.

The problem is not a pressing one. As the up-front investment for PV is high and the operating costs are low, PV power systems do not have a defined end-of-life date but may further produce power beyond their time of financial depreciation. Though, efficiency may diminish slightly after 20 years of continuous operation and sporadic failures of single modules may occur, there is no technical reason for not operating a PV cell for 30 years and more. According to the state-of-the-art of power electronics, the inverter has to be exchanged proactively every ten years during the period of financial depreciation for reasons of maximising the energy fed into the grid. Afterwards, the inverter is assumed to be exchanged only in the presence of failures.

- Cells

The research efforts which have been undertaken by now in the field of thin film PV cells focused on the optimisation and up-scaling of the industrial production process only. Some thin film technologies contain rare and/or toxic substances, such as arsenic, cadmium, gallium or indium. A large-scale application of thin film PV would pose special attention to the development of recycling processes. Considering the uncertainty about the viability of thin film PV technology, the scenarios developed in the framework of this study are thus focused on thick film PV technology.

- Modules

Modules consist of the PV cell itself, string interconnections, substrate, encapsulation and a glass protection on the front-side. The module assembly is usually framed by aluminium profiles, mostly for transportation and less for fastening reasons. Though, the recycling of aluminium is well established, it is widely recommended to deploy frame-less modules for future large-scale applications mostly to diminish the specific primary energy effort (the application of recycled aluminium already diminishes a large amount of the primary energy which is required for primary aluminum production). The company Bayer suggests to apply a frame with/without back plane encapsulation on a polymer basis (poly-urethane) [Bayer 2004].

Substrates (mostly EVA – ethylene vinyl acetate) and encapsulations (such as the brands "Tefzel", "Tedlar" etc.) usually consist of polymers.

- Balance of plant (BOS)

Balance of plant components are required to complement the module for power production purposes. In the framework of this study, only grid-connected PV systems are applied for scenario design. BOS components thus mainly consist of the module support structure, power electronics and cabling.

Support structure

The PV support structure mostly consists of aluminium and/or high-grade steel where there should be no hurdle regarding a large-scale recycling. In case of free space PV power systems, certain amounts of concrete are required as foundation for the fixation of the support structure. Decommissioned concrete is usually applied for the construction of streetways and landfill purposes.

Power electronics and cabling

The recycling of electronics is high on the agenda of the international electronics industry.

The process to develop environmentally benign and easy to recycle power electronics is facilitated by spin-off knowledge gained from technical developments due to EU targets regarding the recycling of automobiles, personal computers, mobile phones and other electronic products. General development lines in the field of electronic products are e.g.

– Lead free connections of electronic components to the circuit board

– Reduction of toxic contents in electronic components as well as toxic substances (such as bromine) which are applied as flame retardant.

The major concern with cabling is their PVC insulation which is the most commonly applied type of cable insulation. This concern mainly bases on three issues:

1. In the course of a fire incident, combustion products of PVC are among others highly toxic dioxin and acidic compounds. From a health point of view this is above all an issue with all cables laid indoor.

2. Pure PVC is hardly applicable for any application. Thus, a broad range of additives are admixed. Sometimes PVC compounds contain up to several dozen percent of additives. These additives often evolve to a certain extend during the application period.

3. The broad variety of PVC compounds is a general hindrance to the development of technologically, economically and ecologically viable PVC recycling processes.

Alternatives to PVC cable insulation have been developed, such as reticulated poly-ethylene.

b) Solar thermal (SOT) power systems

Solar thermal power plants mostly consist of very basic material, such as (high-grade) steel, glass, copper and concrete. In contrary to PV systems (see chapter a)), SOT plants will be owned and operated exclusively by professionals. Furthermore, a single power plant is by far larger in terms of installed capacity (several hundred MW_{inst}). This will result in lower collection efforts compared to widely distributed and privately owned PV systems. Most likely, the SOT plant will be recycled by those companies, who may directly make use of the recycling material, such as companies in the field of steel work and glass manufacturing.

Regarding the materials applied in SOT plants, there seems to be no major hurdle for a large-scale recycling of solar thermal power plant components.

4.6.2 Space solar power systems

The decommissioning / recycling procedure remains unclear, and are not discussed in the "Fresh Look" study report.

The baseline of the "Fresh Look's" Solar Disk calls for refurbishment after 30 years, with replacement fractions of 25%.

Several options are possible of which each requires different prerequisites and results in different impacts on the cost and energy calculation as shown in the table below.

End of life option	Prerequisite	Impact
Controlled die down in atmosphere	None	Lost resources; emissions into the atmosphere
Terrestrial based recycling	Materials applied can be recycled	Cost and energy effort for back haul
Space / Moon based recycling	The materials applied can be recycled. Viability of space / moon based recycling and production facilities.	Cost and energy effort for providing moon based industrial facilities
Disposal orbit	Materials applied can be recycled at an later stage	Cost and energy effort for moving to a higher disposal orbit

Table 4-7: List of principle options of end of life procedures for space systems

[Hazelrigg 1980] states that there would be no realistic chance of bringing material down into the atmosphere from GEO. It would be far more valuable recycled up there – or if not needed it would be put into a higher "disposal orbit", as some GEO satellites are today.

[Hazelrigg 1980] estimated the value of an SPS unit at the end of its life, and found that as a source of spare parts and raw materials its value could be up to 22% of its initial value.

5 COMPARISON OF BASE LOAD SCENARIOS (WP1)

In this chapter a continuous production of base load power is assumed for solar power plants. Terrestrial and space based solar power system concepts are evaluated for a constant power supply over a period of 24 hours per day and 365 days per year independent from actual power demand. A principle sketch of a base load power demand profile is given in Figure 5-1.

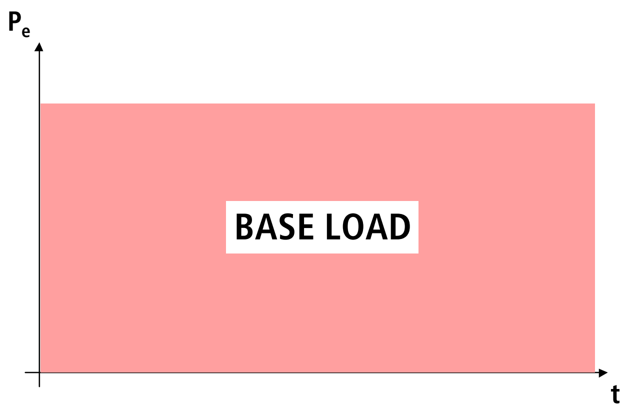


Figure 5-1: Base load operation: continuos, constant power supply.

Terrestrial and space based base load supply scenarios are investigated for the following power levels:

- 0.5 GW_e
- 5 GW_e
- 10 GW_e
- 50 GW_e
- 100 GW_e
- 500 GW_e

To guarantee uninterrupted power supply at these power levels over the whole year (8,760 hours), both concepts are designed with two alternative electricity storage concepts:

- electricity storage via hydrogen (H_2)
- electricity storage via pumped hydro storage.

5.1 Terrestrial concepts

5.1.1 Selected concepts

For base load scenarios solar thermal power plants (SOT) are selected because of their higher solar capacitity factors due to integrated thermal storage compared to photovoltaic (PV). Of all SOT plant concepts central receivers (CR) achieve the highest amount of full load hours of around 6,400 h per year see as was discussed in chapter 2.2.

In all base load scenarios the solar power plants have to supply constant electricity for 8,760 full load hours per year. Therefore the selected central receiver plant (see chapter 2.2.2) with integrated thermal storage is modified and retrofit with additional electricity storage to bridge larger time scales of low solar irradiation. To achieve the target of constant base load operation over the whole year requires electricity storage capacity of about 2,360 h/yr. Electricity, however can be stored in different ways. In this subchapter two different base load system concepts are described: one with electricity storage by means of hydrogen as the storage medium, and the second with electricity storage by pumped water (pumped hydro) as storage medium.

a) SOT plant with electricity storage via H_2

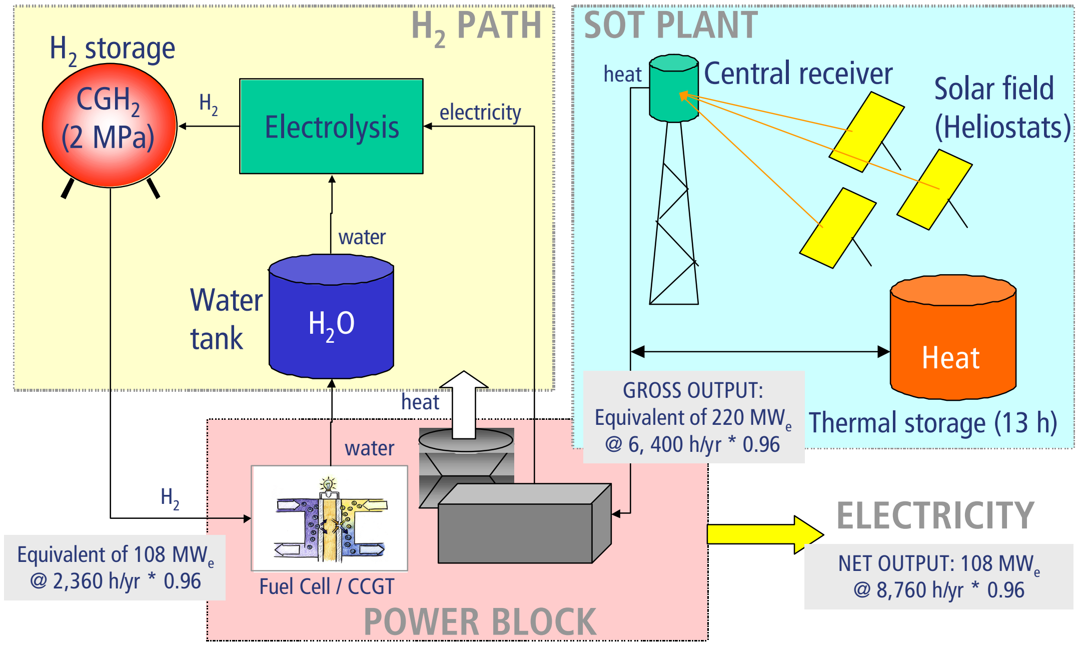


Figure 5-2: Scheme of the SOT plant with thermal and electricity storage via hydrogen

The size of the thermal energy storage of the reference central receiver (CR) plant (see see chapter 2.2) is designed to allow for 13 hours of full load operation. As a result the solar power plant is operated 24 hours per day during summer. The equivalent full load period of the whole solar thermal plant (including local thermal storage but excluding electricity storage via hydrogen) is about 6,400 hours per year. For base load operation, however, the plant should supply constant output at any of the 8,760 hours per year. To bridge that gap during several connected cloudy days hydrogen is used as storage medium. This results in about 2,360 equivalent full load hours per year where the electricity must be supplied from hydrogen by a fuel cell or a combined cycle gas turbine power plant (CCGT). The remaining 6,400 full load hours of the year the power is directly generated by the solar thermal power plant.

For the scenario calculations, this power plant including thermal storage and local hydrogen storage is applied as the 'power module' of choice. Its individual components were already described in preceding chapters, in the course of this chapter it is used like a 'black box' without looking into its details any more.

The idea behind this approach is, to build many identical power modules of several ~100 MW_e respectively 220 MW_e size. Whenever an up-scaling due to higher demand is necessary, this will be done just be increasing the number of modules.

An alternative calculation method would be to collect the electricity of the individual SOT-plants with all the fluctuations as produced. In that situation the smoothing to a continuous power level would be done by one or several large central storage units. The advantage of this concept would be, that part of the fluctuations would already smooth out just by the statistical nature of the fluctuations. Therefore the size of storage system could be reduced. However, a proper treatment of this situation would imply detailed information about the fluctuating behavior and an analysis of the European electricity demand and supply at a disaggregated level which is beyond the scope of the present study. Moreover it would impose a localization of the individual power plants and demand sites at a level, which is not justified for the present study. The chosen analysis based on identical "black box" power modules results in somewhat higher cost levels due to increased requirements for energy storage. Therefore its results represent an upper limit on the expected electricity production cost (conservative approach).

Plant shut down for maintenance is scheduled with 14 days per year. This results in reduced operation time of 8,400 hours per year, equivalent to a capacity factor of 0.96. Just for comparison, an equivalent full load period of 8,400 hours per year is typical for refineries.

There is a large number of plants, and the time for maintenance of different plants is temporally shifted. Therefore the 8,760 hours can be achieved simply by increasing the number of plants.

The hydrogen storage is one of the major cost parts of the hydrogen concept. Figure 5-3 shows the cost influence and split of a SOT plant designed for different hydrogen storage capacities. The left diagram shows a system with electricity storage via hydrogen planned for maximum hydrogen supply for a duration of nearly two days: In the event of power failure of the solar power plant the fuel cell / combined gas turbine could supply 100 % of the nominal plant power (108 MW_e) for 1.9 days. In the second diagram on the left side the storage capacity is increased. This system could provide electricity generated by FC/CCGT via hydrogen for 19 days without the system part of the SOT plant.

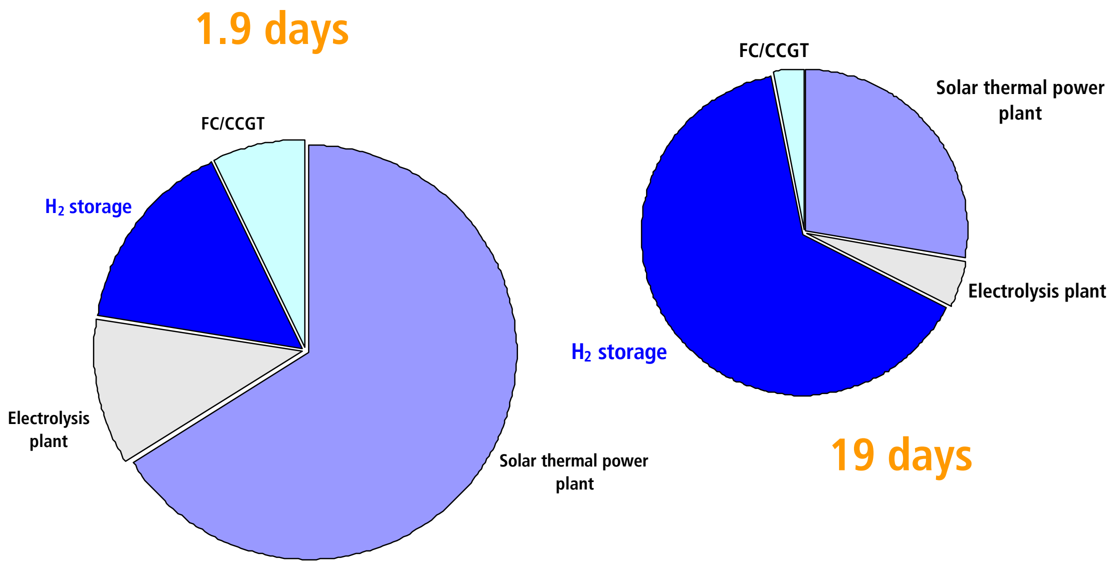


Figure 5-3: Split of investment costs of the SOT plants with electricity via hydrogen (H_2, storage, FC/CCGT, electrolysis plant), depending on hydrogen storage capacity: cost comparison for plant with capacity of 1.9 days and 19 days

The figure above shows the effect of a large hydrogen storage. For low investment costs it is important to design for the terrestrial scenarios, modules with small individual hydrogen storage. For the base load scenarios the storage capacity of 1.9 days has been selected in order to guarantee high reliable power supply over the whole year (cloudy days, sandstorms etc.). With higher power levels (0.5 GW → 5 GW → 10 GW → 50 GW → 100 GW → 500 GW) the need of large hydrogen storage capacities of the single terrestrial SOT plants is reduced. The total installed hydrogen storage capacity at all installed SOT plants, each with small local storage capacities (~ 1.9 days), can be added to a large virtual storage. All these SOT plants are distributed in zone 1 (European sunbelt), and for the 500 GW scenarios also throughout zone 0 (North Africa). So it can be assumed that a power failure over the total zone 1 or zone 0 for more than 3 days (H_2 storage + thermal storage of the SOT) is very unlikely.

Figure 5-4 shows the total calculated cost for the base load optimized central receiver plant with electricity storage via hydrogen depending on the storage size.

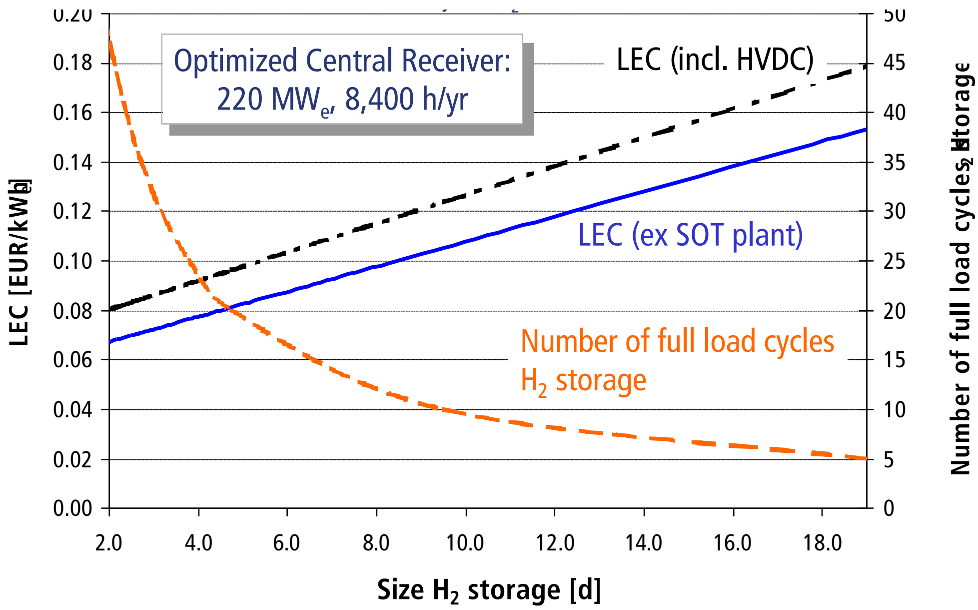


Figure 5-4: LEC for base load optimized central receiver plant depending on hydrogen storage size with and without (ex SOT plant) power transmission via HVDC

Table 5-1 lists relevant design parameters for base load optimized SOT plant. These data are based on the reference model of the 220 MW$_e$ central receiver plant with integrated thermal storage as described in 2.2. General data and technology assumptions for the hydrogen storage concerning electrolyzer or fuel cell/CCGT were given in Table 5-1.

Maximum electricity output SOT_gross	220 MW$_e$
Maximum electricity output SOT plant_net	108 MW$_e$
Maximum electricity output FC/CCGT_net	108 MW$_e$
Required land area per plant (zone 0)	13.9 km² / plant
Required land area per plant (zone 1)	22.5 km² / plant
Annual full load hours	8,400 h/yr

Table 5-1: Technical data for base load optimized SOT plant with electricity storage via H_2

Therefore, the required land area for the SOT plant in zone 1 (European sunbelt) must be increased according to the lower solar irradiation. The reference plant was originally planned for higher solar irradiation than in southern Europe.

Further scenario specific data which depend on the installed SOT capacity are listed in the following chapters, see 5.1.3.

b) SOT plant with electricity storage via pumped hydro

The concept of a SOT plant with electricity storage via pumped hydro is similar to the concept with a hydrogen storage. The reference SOT plant with a central receiver and thermal storage defined in chapter 1.2. generates electricity for ~ 6,400 full loads hours per year. Consequently, the electricity storage via pumped hydro has to bridge about 2,360 h/yr. Planned plant shut downs for maintenance reduce the equivalent capacity factor of 0.96 resulting in ~ 8,400 h/yr operating hours.

Table 5-2 sketches the scheme of the base load optimized SOT plant with electricity storage via pumped hydro.

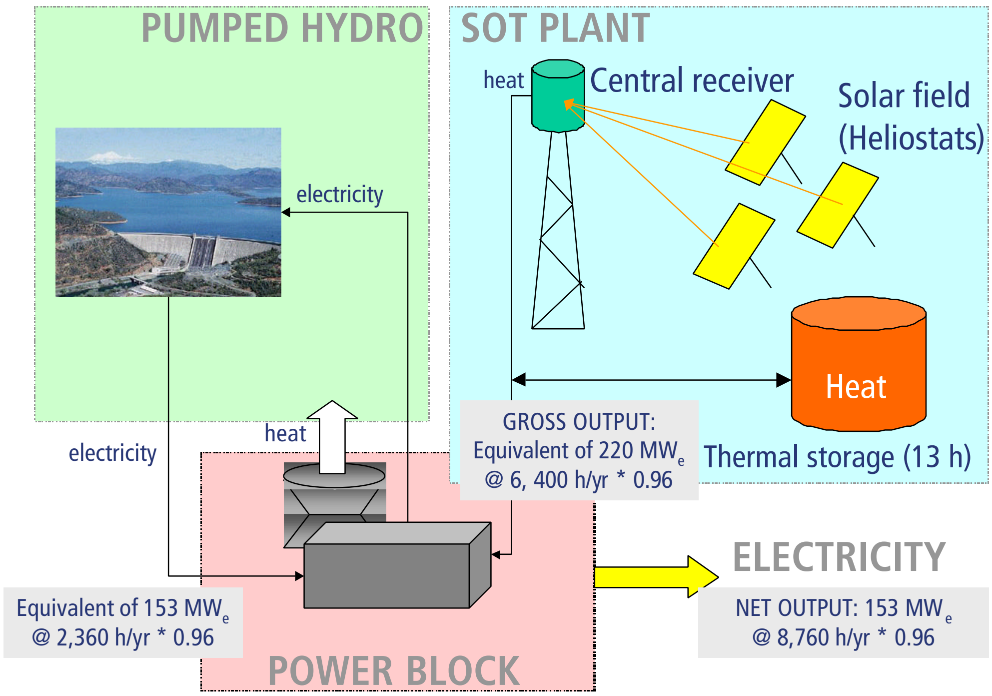


Figure 5-5: Scheme of the SOT plant with thermal storage and electricity storage via pumped hydro

Because of lower losses due to the additional electricity storage the net electricity output of the system is higher compared to the hydrogen storage variant (see Table 5-2).

Maximum electricity output SOT_gross	220 MW_e
Maximum electricity output SOT plant_net	153 MW_e
Maximum electricity output FC/CCGT_net	153 MW_e
Required land area per plant (zone 0)	13.9 km^2/plant
Required land area per plant (zone 1)	22.5 km^2/plant
Annual full load hours	8,400 h/yr

Table 5-2: Technical data for base load optimized SOT plant with electricity storage via pumped hydro

5.1.2 Scenario data

In the this chapter technical data for each base load scenario are presented for terrestrial concepts with:

a) electricity storage via hydrogen with 220 MW_e central receiver solar power plant modules which supply 108 MW_e each

and with

b) electricity storage via pumped hydro with 220 MW_e central receiver solar power plant modules which supply 153 MW_e each.

More detailed technical assumptions concerning installed capacities, energy storage means and high-voltage power transmission are discussed in the Report Annex (see chapter A2).

Figure 5-6 to Figure 5-9 depicts the resulting SOT installations in zone 0 and zone 1 depending on the storage technology applied.

a) Scenario 0.5 GW

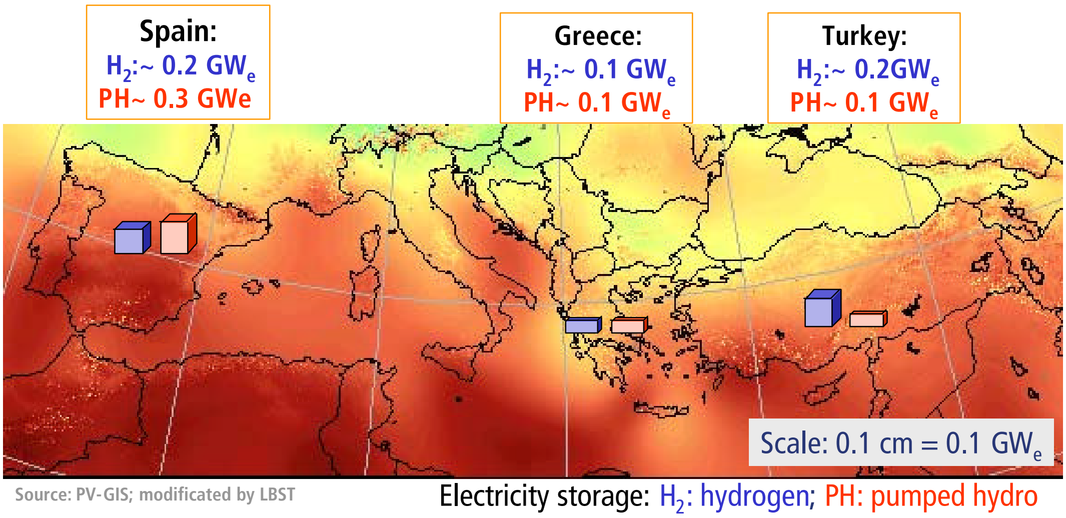


Figure 5-6: Installed SOT plant capacities in zone 1 for 0.5 GW scenarios with electricity storage H_2 / pumped hydro

b) Scenarios 5 GW

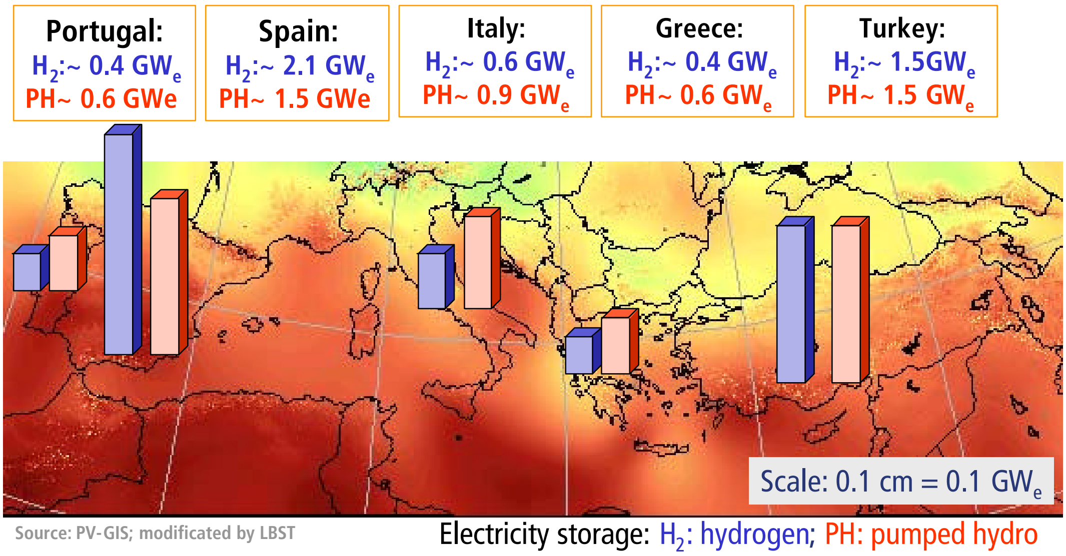


Figure 5-7: Installed SOT plant capacities in zone 1 for 5 GW scenarios with electricity storage H_2 / pumped hydro

c) **Scenario 10 GW**

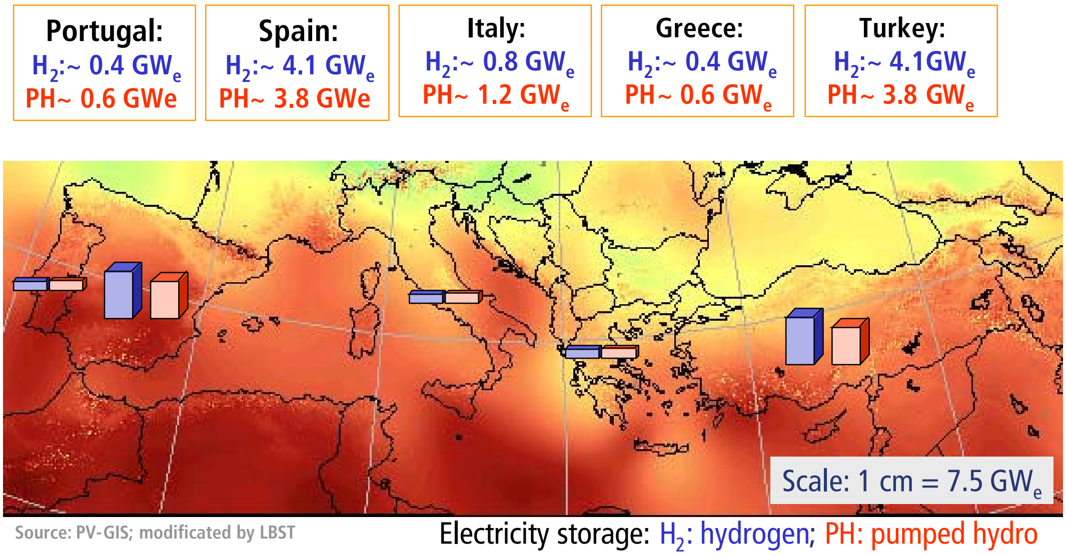


Figure 5-8: Installed SOT plant capacities in zone 1 for 10 GW scenarios with electricity storage H_2 / pumped hydro

d) **Scenario 50 GW**

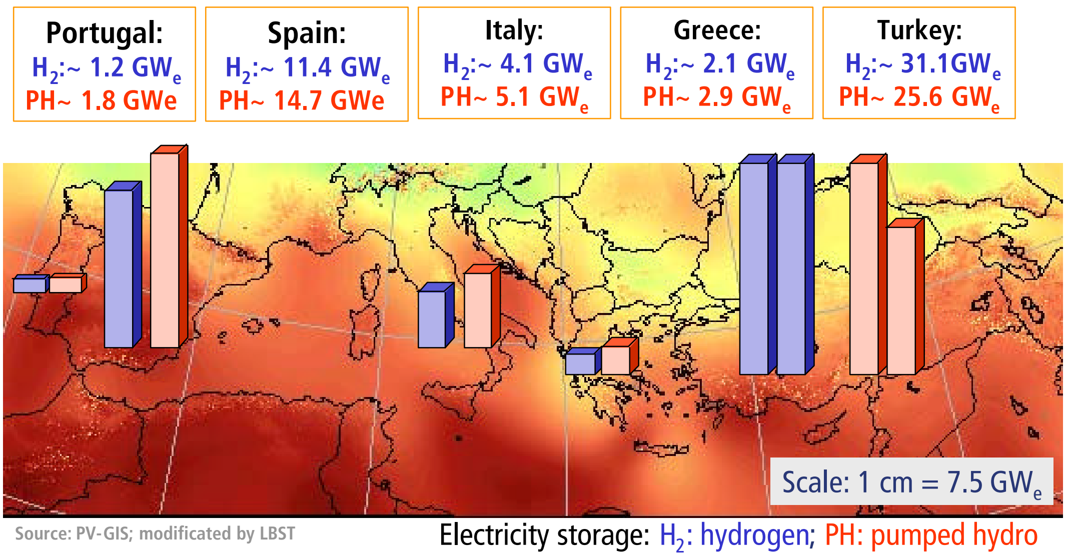


Figure 5-9: Installed SOT plant capacities in zone 1 for 50 GW scenarios with electricity storage hydrogen / pumped hydro storage

e) Scenario 100 GW

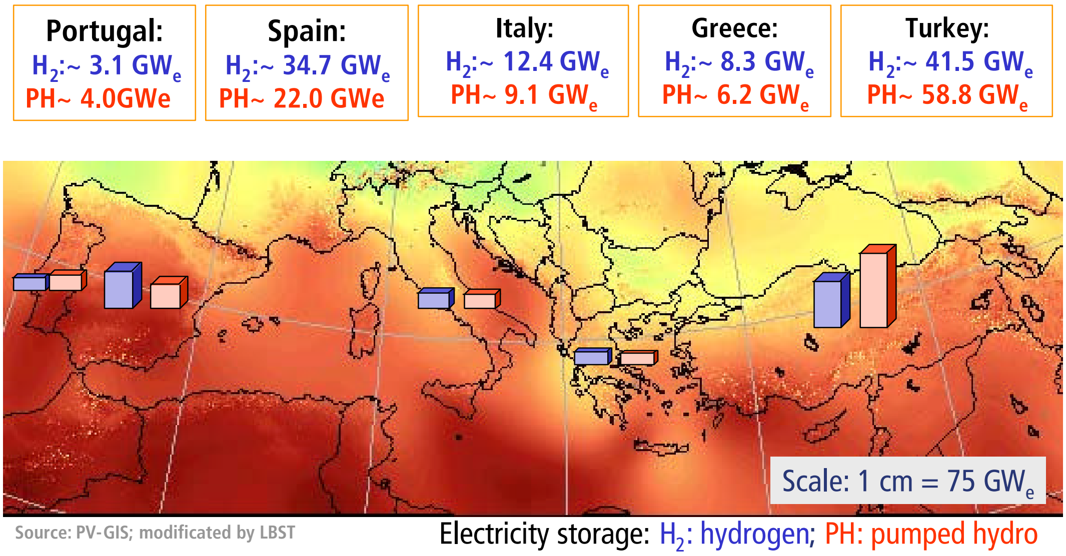


Figure 5-10: Installed SOT plant capacities in zone 1 for 100 GW scenarios with electricity storage H_2 / pumped hydro

f) Scenario 500 GW

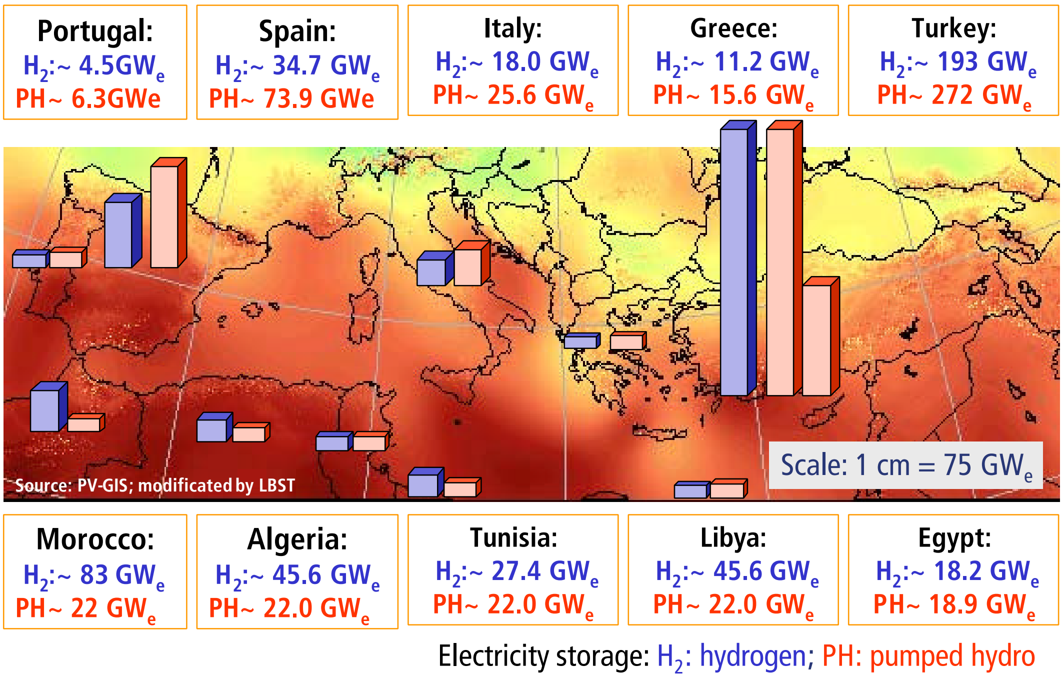


Figure 5-11: Installed SOT plant capacities in zone 1 for 500 GW scenarios with electricity storage hydrogen / pumped hydro

The following figures show the resulting amounts of power which have to be transmitted via HVDC from zone 1 and zone 0 into zone 2 for the 500 GW scenarios. Figure 5-12 shows the power transmission via HVDC for the terrestrial concept with electricity storage via hydrogen and Figure 5-13 shows the results for electricity storage via pumped hydro.

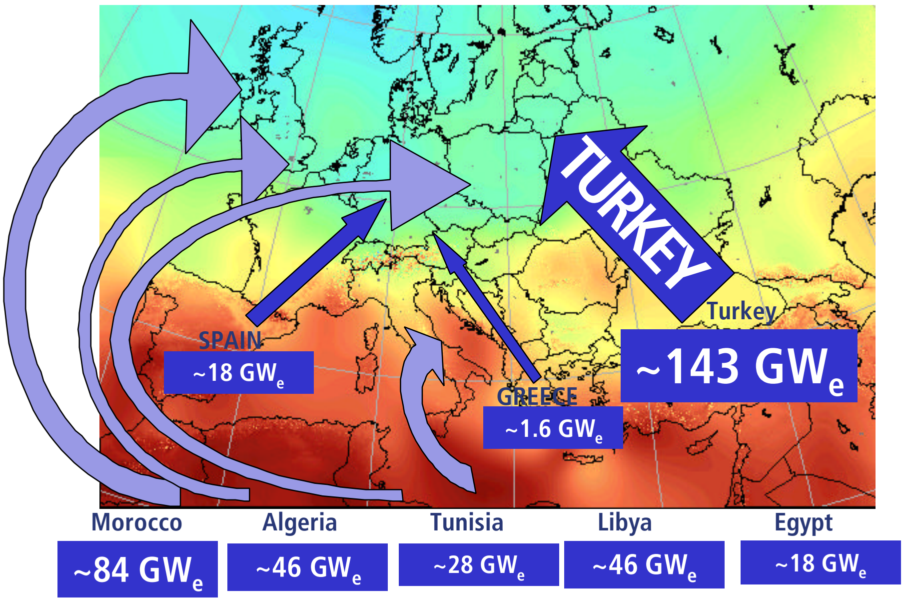


Figure 5-12: Required power transmission from zone 0 (North Africa) and zone 1 (European sunbelt) via HVDC for 500 GW scenario with electricity storage via H_2

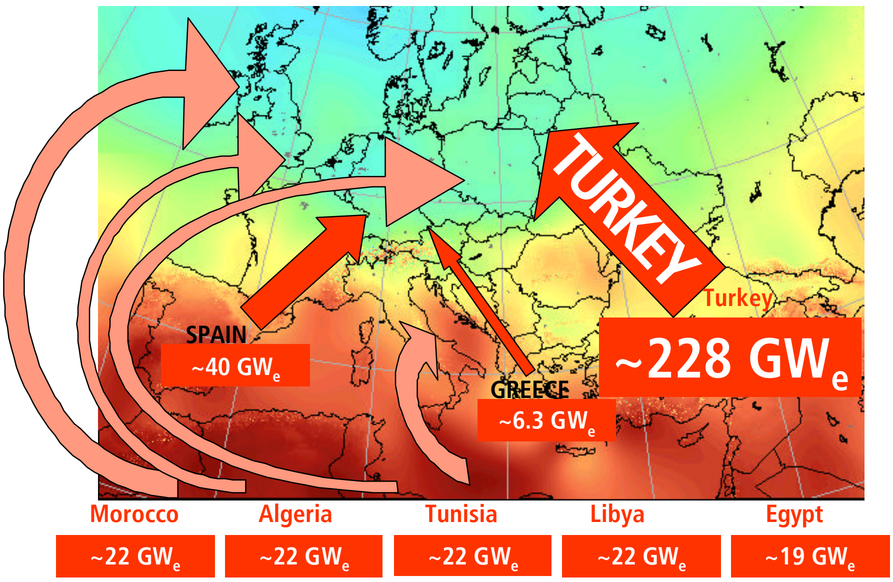


Figure 5-13: Required power transmission capacities from zone 0 (North Africa) and zone 1 (European sunbelt) via HVDC for 500 GW scenario with electricity storage via pumped hydro

In all other scenarios with lower power levels described above no additional power transmission via HVDC is required. Only for 500 GW base load HVDC are needed.

5.1.3 Costs

In the following calculated costs and their assumptions are presented for terrestrial concepts with electricity storage via hydrogen and pumped hydro.

a) Electricity storage via H_2

Table 5-3 shows assumptions for cost data calculations and levelized electricity costs (LEC).

	Unit	0.5 GW	5 GW	10 GW	50 GW	100 GW	500 GW
Maximum electricity output SOT	MW	220	220	220	220	220	220
Investment	EUR	688,900,000	601,300,000	578,800,000	532,100,000	514,300,000	477,300,000
Specific investment electrolysis	EUR/kW_{H2}	500	500	500	500	500	500
Efficiency electrolyzer		65%	65%	65%	65%	65%	65%
Maximum electricity input electrolyzer	MW_e	112	112	112	112	112	112
Investment electrolysis plant	EUR	86,000,000	86,000,000	86,000,000	86,000,000	86,000,000	86,000,000
Required storage capacity	d	1.9	1.9	1.9	1.9	1.9	1.9
Number of loading unloading cycles		50	50	50	50	50	50
Required net storage capacity	Nm^3 H_2	2,984,425	2,984,425	2,984,425	2,984,425	2,984,425	2,984,425
Max. pressure	bar	20	20	20	20	20	20
Min. pressure	bar	2	2	2	2	2	2
Specific gross storage capacity	Nm^3/l	0.018	0.018	0.018	0.018	0.018	0.018
H_2 remaining in storage	Nm^3/l	0.002	0.002	0.002	0.002	0.002	0.002
Specific net storage capacity	Nm^3/l	0.016	0.016	0.016	0.016	0.016	0.016
storage utilization		90%	90%	90%	90%	90%	90%
Required storage	l	181,456,990	181,456,990	181,456,990	181,456,990	181,456,990	181,456,990
Storage volume per spherical pressure vessel	l	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000
Specific investment	EUR/unit	1,917,345	1,917,345	1,917,345	1,917,345	1,917,345	1,917,345
Number of spherical pressure vessels		60	60	60	60	60	60
Investment hydrogen storage	EUR	116,000,000	116,000,000	116,000,000	116,000,000	116,000,000	116,000,000
Efficiency FC/CCGT		55%	55%	55%	55%	55%	55%
Specific investment FC/CCGT	EUR/kW_e	500	500	500	500	500	500
Maximum electricity output FC	**MW_e**	**108**	**108**	**108**	**108**	**108**	**108**
Electricity generated by FC/CCGT	kWh_e/yr	246,215,073	246,215,073	246,215,073	246,215,073	246,215,073	246,215,073
Equivalent full load period FC/CCGT	h/yr	2,283	2,283	2,283	2,283	2,283	2,283
Technical availability		0.96	0.96	0.96	0.96	0.96	0.96

	Unit	0.5 GW	5 GW	10 GW	50 GW	100 GW	500 GW
Electricity generation total	**MWh_e/ (30 yr)**	**27,256,281**	**27,256,281**	**27,256,281**	**27,256,281**	**27,256,281,**	**27,256,281**
Investment SOT	EUR	688,900,000	601,300,000	578,800,000	532,100,000	514,300,000	477,300,000
Investment electrolysis plant	EUR	86,000,000	86,000,000	86,000,000	86,000,000	86,000,000	86,000,000
Investment storage	EUR	116,000,000	116,000,000	116,000,000	116,000,000	116,000,000	116,000,000
Investment FC/CCGT	EUR	53,925,849	53,925,849	53,925,849	53,925,849	53,925,849	53,925,849
Total	**EUR**	**944,825,849**	**857,225,849**	**834,725,849**	**788,025,849**	**770,225,849**	**733,225,849**
Share equity		1	1	1	1	1	1
Share dept		0	0	0	0	0	0
IRR		6.0%	6.0%	6.0%	6.0%	6.0%	6.0%
Interest rate dept		6.0%	6.0%	6.0%	6.0%	6.0%	6.0%
Useful lifetime	yr	30	30	30	30	30	30
Dept term	yr	30	30	30	30	30	30
Capital costs	**T EUR/ (30 yr)**	**2,059,217**	**1,868,295**	**1,819,257**	**1,717,476**	**1,678,682**	**1,598,041**
Insurance	of investment/yr	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
Insurance	EUR/(30 yr)	141,723,877	128,583,877	125,208,877	118,203,877	115,533,877	109,983,877
O&M SOT	EUR/kWh_e	0.003	0.003	0.003	0.003	0.003	0.003
O&M SOT	EUR/(30 yr)	126,443,592	126,443,592	126,443,592	126,443,592	126,443,592	126,443,592
O&M electrolyzer	of investment/yr	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%
O&M electrolyzer	EUR/(30 yr)	38,700,000	38,700,000	38,700,000	38,700,000	38,700,000	38,700,000
O&M Fuel cell/CCGT	EUR/(30 yr)	73,864,522	73,864,522	73,864,522	73,864,522	73,864,522	73,864,522
Electricity costs	**EUR/kWh_e**	**0.090**	**0.082**	**0.080**	**0.076**	**0.075**	**0.071**

Table 5-3: Calculated electricity costs of SOT plants for base load scenarios with electricity storage via H_2 (without HVDC)

Figure 5-14 shows the resulting LEC of the base load optimized SOT plant with integrated hydrogen storage. The different resulting costs base on the different assumptions and predictions for SOT plant development of [S&L 2003], see also chapter 3. LEC SOT (min) bases on technology and cost assumptions of "SunLab" and LEC SOT (bandwidth) on predictions and calculations of "Sargent&Lundy".

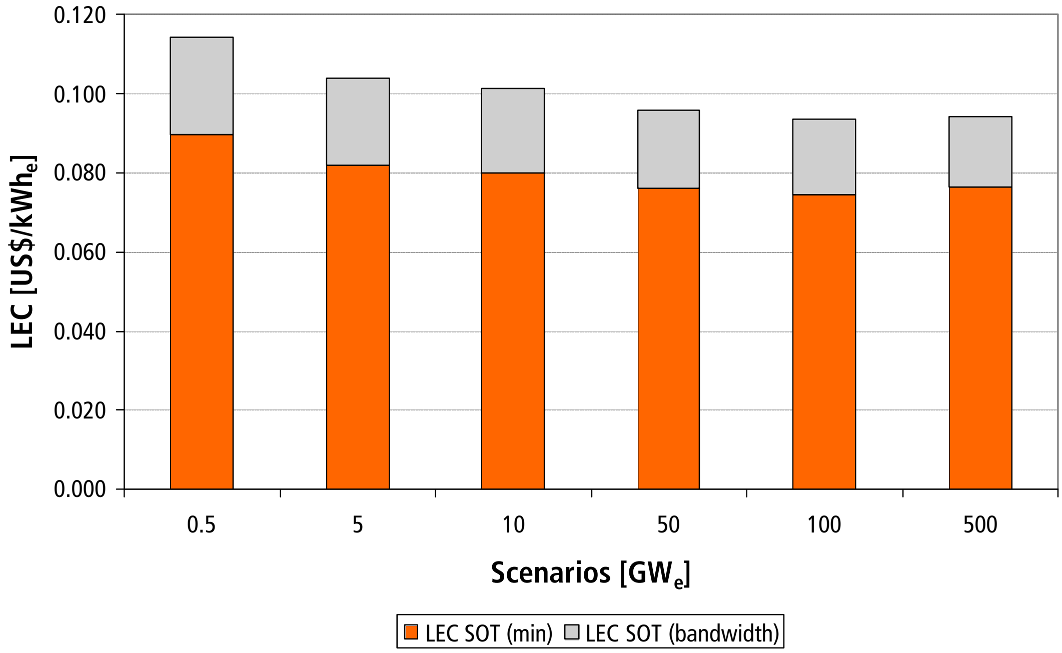


Figure 5-14: LEC of terrestrial SOT with electricity storage via hydrogen with range of uncertainty

For further comparisons LEC SOT (min) was selected as reference concept, see therefore also discussion in chapter 3. The diagram in Figure 5-15 bases on data for LEC SOT (min) with a primary SOT reference system from "SunLab" [S&L 2003].

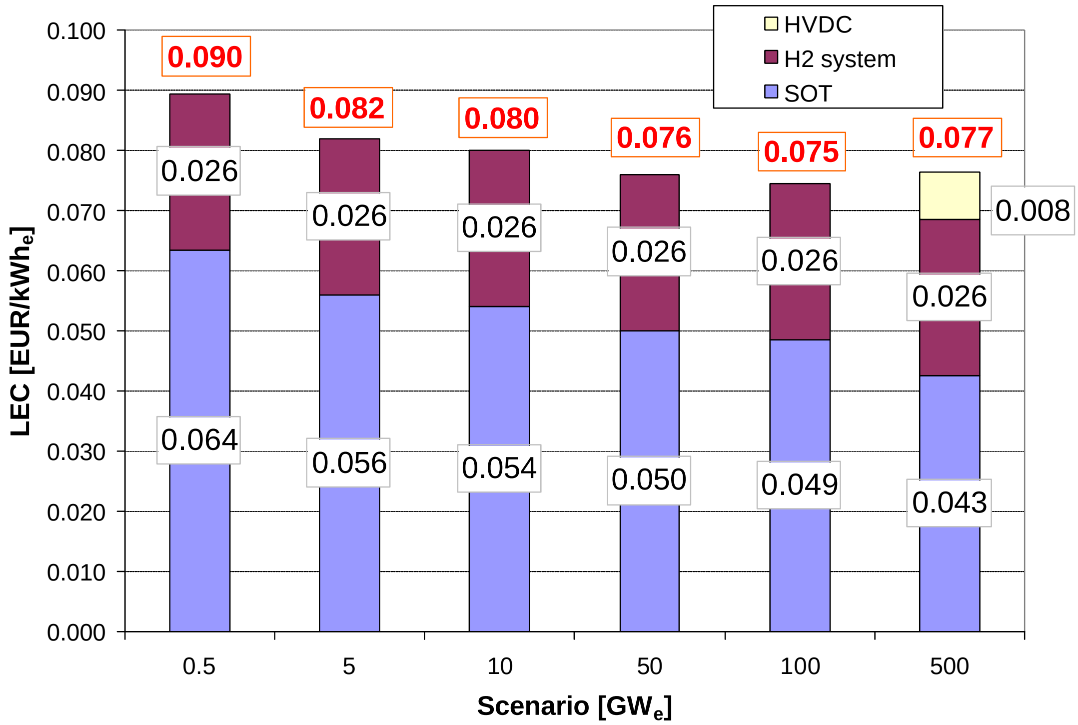


Figure 5-15: Split of LEC of terrestrial SOT with electricity storage via H_2 (min)

The diagram above provides an overview of the cost split of the SOT systems for all terrestrial base load scenarios.

The cost reduction of the SOT plant with higher power levels results from the increased amount of installed central receiver plants in scenarios with higher power levels. Specific information about cost reduction respectively learning curves of central receiver plants are described in the previous part of the study, chapter 2.2. The cost part of the H_2 part increase from 29 % for 0.5 GW to 35 % for 100 GW and achieves 34 % in the 500 GW scenario which also includes 10 % transmission costs via HVDC. For terrestrial base load lowest LEC of 0.075 EUR/kWh$_e$ are achieved in the 100 GW scenario due to higher transmission costs in the 500 GW scenario.

A split of LEC for all power levels are listed in chapter 5.3.2 Cost.

b) Electricity storage via pumped hydro

Table 5-4 shows assumptions for cost data calculations and levelized electricity costs (LEC).

	Unit	0.5 GW	5 GW	10 GW	50 GW	100 GW	500 GW
Maximum electricity output SOT	MW	220	220	220	220	220	220
Investment	EUR	703,100,000	612,700,000	589,400,000	541,100,000	522,600,000	484,400,000
Power specific investment pumping storage	EUR/kWe	600	600	600	600	600	600
Energy specific investment pumping storage	EUR/kWhe	12	12	12	12	12	12
Efficiency pumping storage		85%	85%	85%	85%	85%	85%
Maximum electricity pump	MW_e	67	67	67	67	67	67
Investment pumping storage plant	EUR	192,000,000	192,000,000	192,000,000	192,000,000	192,000,000	192,000,000
Required storage capacity	d	1.9	1.9	1.9	1.9	1.9	1.9
Number of loading/unloading cycles		50	50	50	50	50	50
Required net storage capacity	kWhel	6,988,431	6,988,431	6,988,431	6,988,431	6,988,431	6,988,431
Maximum electricity output pumping storage plant	**MW_e**	**153**	**153**	**153**	**153**	**153**	**153**
Electricity generated by pumping storage plant	kWh_e/yr	349,421,571	349,421,571	349,421,571	349,421,571	349,421,571	349,421,571
Equivalent full load period pumping storage plant	h/yr	2,283	2,283	2,283	2,283	2,283	2,283
Technical availability		0.96	0.96	0.96	0.96	0.96	0.96
Electricity generation total	**MWh_e/ (30 yr)**	**38,681,355**	**38,681,355**	**38,681,355**	**38,681,355**	**38,681,355**	**38,681,355**
Investment SOT	EUR	703,100,000	612,700,000	589,400,000	541,100,000	522,600,000	484,400,000
Investment pumping storage plant	EUR	192,000,000	192,000,000	192,000,000	192,000,000	192,000,000	192,000,000
Total	**EUR**	**895,100,000**	**804,700,000**	**781,400,000**	**733,100,000**	**714,600,000**	**676,400,000**
Share equity		1	1	1	1	1	1
Share dept		0	0	0	0	0	0
IRR		6.0%	6.0%	6.0%	6.0%	6.0%	6.0%
Interest rate dept		6.0%	6.0%	6.0%	6.0%	6.0%	6.0%
Useful lifetime	yr	30	30	30	30	30	30
Dept term	yr	30	30	30	30	30	30
Capital costs	**T EUR/ (30 yr)**	**1,950,841**	**1,753,817**	**1,703,036**	**1,597,768**	**1,557,447**	**1,474,192**
Insurance	of investment/yr	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
Insurance	EUR/(30 yr)	134,265,000	120,705,000	117,210,000	109,965,000	107,190,000	101,460,000
O&M SOT	EUR/kWh_e	0.003	0.003	0.003	0.003	0.003	0.003
O&M SOT	EUR/(30 yr)	126,443,592	126,443,592	126,443,592	126,443,592	126,443,592	126,443,592
O&M pumping storage plant	EUR/kWhe	0.004	0.004	0.004	0.004	0.004	0.004
O&M pumping storage plant	EUR/(30 yr)	41,930,588	41,930,588	41,930,588	41,930,588	41,930,588	41,930,588
Electricity costs	**EUR/kWh_e**	**0.058**	**0.053**	**0.051**	**0.049**	**0.047**	**0.045**

Table 5-4: Calculated electricity costs of SOT plants for base load scenarios with electricity storage via pumped hydro (without HVDC)

Figure 5-16 shows the resulting LEC of the base load optimized SOT plant with integrated pumped hydro storage. The different resulting costs base on the different assumptions and predictions for SOT plant development of [S&L 2003] (see also chapter 2.2). LEC SOT (min) base on technology and cost assumptions of "SunLab" and LEC SOT (bandwidth) on predictions and calculations of "Sargent&Lundy".

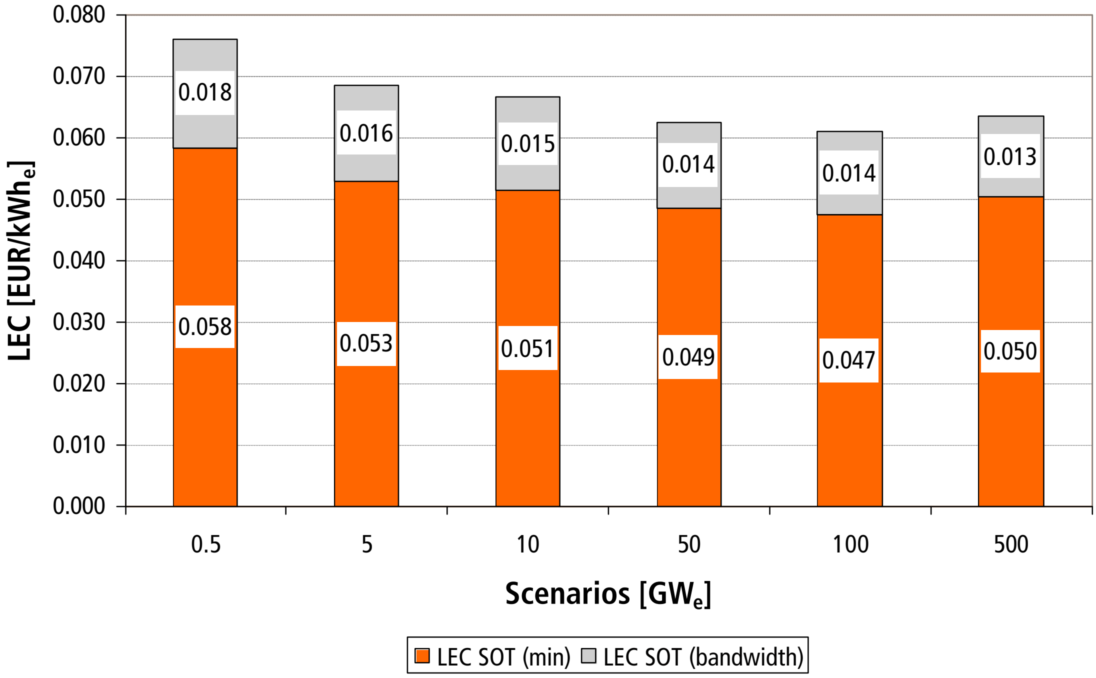


Figure 5-16: LEC of terrestrial SOT with electricity storage via pumped hydro with range of uncertainty

For further comparisons, LEC SOT (min) was selected as reference concept (see also discussion in chapter 2.2.2). The diagram in Figure 5-17 bases on data for LEC SOT (min) with a primary SOT reference system from "SunLab" [S&L 2003].

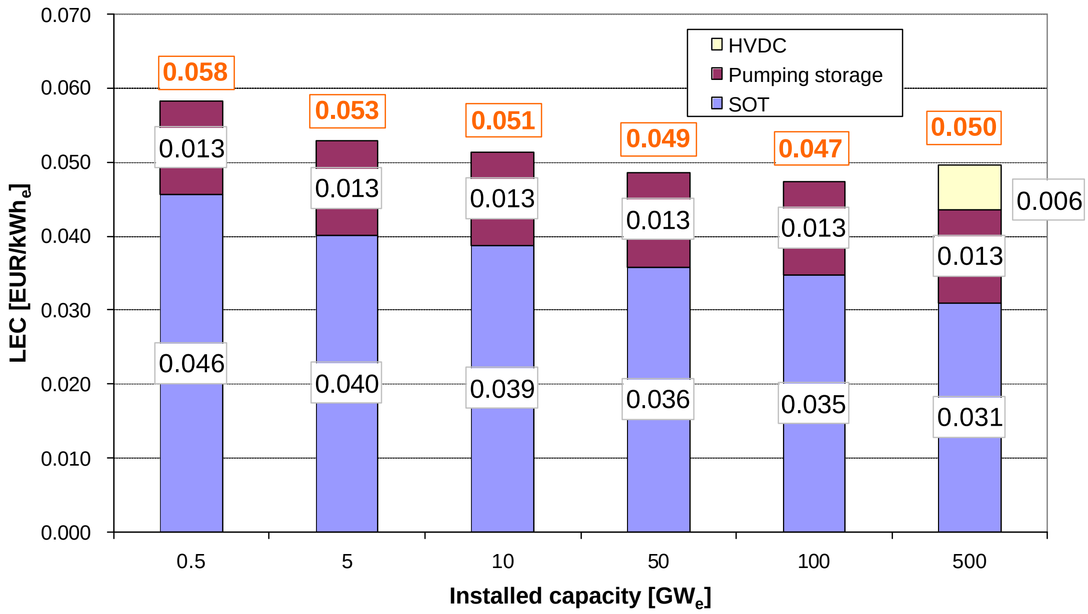


Figure 5-17: Split of LEC of terrestrial SOT with electricity storage via pumped hydro (min)

The diagram above provides an overview of the cost split of the SOT systems for all terrestrial base load scenarios.

The cost reduction of the SOT plant with higher power levels results from the increased amount of installed central receiver plants in scenarios with higher power levels. Specific information about cost reduction respectively learning curves of central receiver plants are described in the previous part of the study, chapter 2.2. The cost part of the H_2 part increase from 22 % for 0.5 GW to 27 % for 100 GW and achieves 25 % in the 500 GW scenario which also includes 13 % transmission costs via HVDC. For terrestrial base load lowest LEC of 0.047 EUR/kWh$_e$ are achieved in the 100 GW scenario due to higher transmission costs in the 500 GW scenario.

A split of LEC for all power levels are listed in chapter 5.3.2 Cost.

5.2 Space concepts

5.2.1 Selected concepts

A brief description of selected space concepts is given in chapter 3.2. In this chapter the selected space concepts for base load scenarios are described for each specific power level (0.5 GW / 5 GW / 10 GW / 50 GW / 100 GW / 500 GW).

- Approach

Initially, basing on the material referenced in the SOW, the choice fell on the NASA "Fresh Look" Study, as a source for data for the different specified power-level scenarios. Following the discussions at the Workshop I, other potential sources received some attention, but we eventually decided to remain with the "Fresh Look" database, because it offered a consistent of cases from which to select the rough configurations for the different scenarios, against the relative dearth of data (with variable) assumptions that could be obtained from other studies.

In the Phase II of the "Fresh Look" Study, the researchers investigated various architectures in an effort to reduce the "cost to first power" and to assess the potential of power stations on orbits other than geostationary. The results did not appear too supportive for novel architectures: in particular, all cases with LEO or MEO stations using relay satellites exhibited a negative undiscounted NPV. Similar (or marginal) results came from those configurations employing a single Sun Tower station. Just as unsurprisingly, single-station architectures using GEO units showed a parallel trend.

- Development timeline

The basic assumptions concern a 5-year development time, with the first power satellite deployed in year 7.

- Eclipse seasons

Satellites in geostationary orbit enter the Earth's shadow during two 43-day periods around the spring and fall equinoxes. The eclipse duration grows from zero up to almost 72 min: time within the umbra is about 94.1%, the remaining 5.9% consisting of the transits through the penumbra. Accordingly, within the accuracy bounds used for the present study, one can assert that the longest eclipse time for a single satellite will reach 70 min. Further, through consideration of the umbra's angular width (16.81° in the equatorial plane), we can determine whether a single or several SPS find themselves eclipsed at the same time. Table 5-5 collects the results for the different scenarios discussed above, in particular giving the power to be extracted from the storage, the highest energy defect to be compensated through the storage, and the highest rate at which the energy store needs to be replenished: this corresponds only to 1.3-2.6% of the scenario's installed power level.

Scenario	5 GW	10 GW	50 GW	100 GW	500 GW
Number of space power plants	5	2	10	20	50
Maximum eclipse duration	70 min				
Plants spacing in orbit	12.5°	50°	5.56°	2.63°	1.02°
Number of plants eclipsed simultaneously	2	1	4	7	17
Eclipse time overlap between leading & trailing plant	17.2 min	0	0.6 min	4.1 min	1.9 min
Maximum relative power drop	40%	50%	40%	35%	34%
Storage power rating	2 GW	5 GW	20 GW	35 GW	170 GW
Maximum energy defect	21 TJ	42 TJ	210 TJ	420 TJ	2100 TJ
Maximum accumulation rate	259 MW	511 MW	2556 MW	5125 MW	25583 MW

Table 5-5: Eclipse-related parameters for the different scenarios

A further source of power outages derives from the reciprocal shadowing of the satellite power plants. Again, this can only occur – during a smaller number of days – within the eclipse season, around subsatellite times corresponding to 06:00 and 18:00. Examination of the geometrical relationships for the different architectures shows that eclipsing by other satellites applies only to the 500 GW scenario: then plants may lose about 65% of their power generation capacity for times up to no more than 15 min.

To guarantee a continuous power supply from the SPS system an additional storage is included into the SPS concept to bridge these power outages. Two different storage options are selected as described before in chapter 4.4 "Energy storage" and 5.1 "Terrestrial concepts":

a) SPS with electricity storage via hydrogen

and

b) SPS with electricity storage via pumped hydro.

Both storage concepts are equivalent to terrestrial concepts and installed on-site the rectennae.

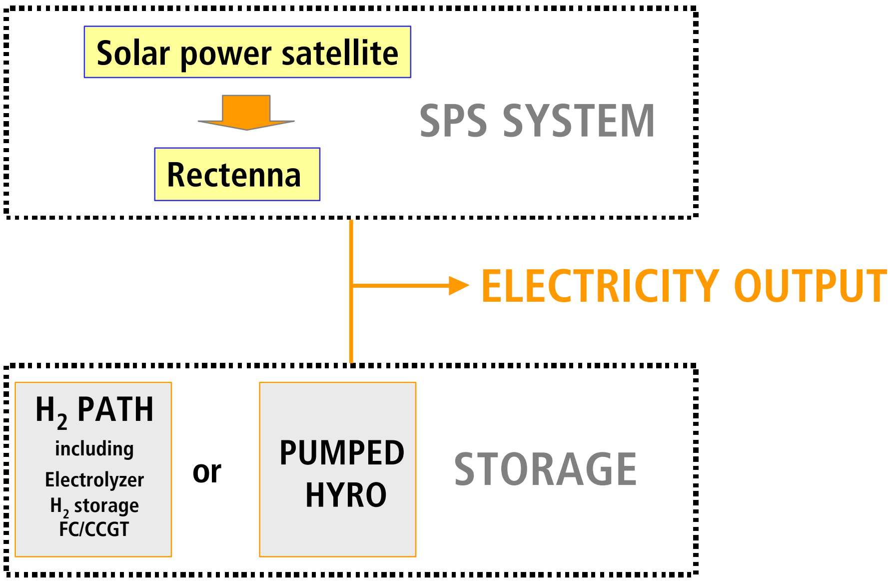


Figure 5-18: Scheme of the SPS concepts with two storage options

Electricity from space based power systems are fed from the rectennae into the European electricity grid. For required power transmission above 10 GW_e additional HVDCs are required (see chapter 4.3 European grid respectively chapter 5.1 "Terrestrial concepts":). For the calculation of the required amount of power transmission the regional power consumption is also allocated.

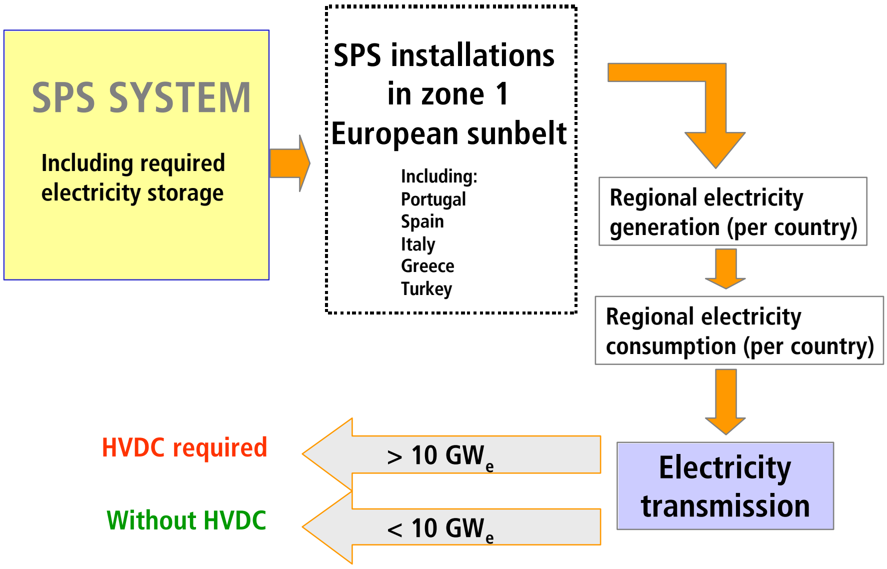


Figure 5-19: Scheme of scenario calculation (siting and electricity calculation)

As Figure 5-19 shows, SPS rectennae and storage are installed in the zone 1 (European sunbelt). For required electricity transmission via HVDC throughout rest of Europe (zone 2) the regional power consumption is taken into account to reduce the required amount of power transmission.

5.2.2 Scenario refence systems

- Scenario 0.5 GW

Eight 250-MW NASA 'Sun Tower' are selected as reference for the present scenario. Such an approach eliminates any need for storage during satellites' eclipses.

Power is delivered to 2 rectennae of about 2-km diameter each, estimated for a 200 W/m^2 average power density in the microwave beam. This is significantly more conservative than the 350 W/m^2 value that can be read out of the "Fresh Look" data. The land requirement includes a 1-km wide buffer zone around the rectenna plant proper.

See more discussion about reference system selection in Report Annex A2.2.

- Scenario 5 GW

As for the previous scenario, this power level can be provided through a single station or through a constellation of smaller power plants. To consider the Sun Tower MEO option, we have used the data from the configurations interpolated for the previous scenario, scaling the procurement costs linearly, i.e. neglecting any improvement associated with a learning curve. Furthermore, given the negative correlation of cost with size, we have refrained to consider a 5-GW extrapolation. Similarly, data were compiled for Solar Disk stations over the range of power levels, up to the standard 5-GW case. The data are presented in Report Annex (see chapter A2).

In terms of procurement costs alone, the GEO Solar Disk exhibits a clear advantage – being lower by at least a factor of four. The orbited mass is also significantly lower, leading to the choice of five 1-GW Solar Disks as space segment option for this scenario. The separation would amount to 12.5°.

In this scenario, the power is delivered to five rectennae, all located in the "European sun belt" zone: a 40° latitude was used to estimate their extension.

- Scenario 10 GW

For this power level – as for the subsequent scenarios – the good scaleability of the Solar Disk design immediately suggests the use of two 5-GW units to provide the necessary power level.

In the basic scenario, two rectennae around 40° latitude receive to power.

- Scenario 50 GW

Ten 5-GW Solar Disk stations provide the required power level.

The power is extracted through 10 rectennae, with 8 assumed positioned around 40° and 2 around 45° latitude.

- Scenario 100 GW

Twenty 5-GW Solar Disk stations provide the required power level. A move to the (postulated) 10-GW maximum power level for that station concept, with a corresponding drop in number of orbital plants, may become attractive for this and for the next scenario, to space the SPS more widely. The European orbital arc extends typically from 15°W (touching the oriental end of Iceland) to 35°E longitude (covering all of Finland and taking in most of Turkey), or a total of 50°. Accordingly, twenty SPS spaced equally would have a separation of some 2.6°, ten plants of 5.5°.

The power is extracted through 20 rectennae, with 16 assumed positioned around 40° and 4 around 45° latitude.

- Scenario 500 GW

Fifty 10-GW Solar Disk stations – a separation of about 1° – provide the required power level. See further details in the Report Annex (see chapter A2).

The power of 50 solar power satellites is transmitted to 100 rectennae. Each rectenna requires a land area of around 80 km². Figure 5-20 shows the assumed distribution of rectennae along the 40°, 45° and 50° latitudes.

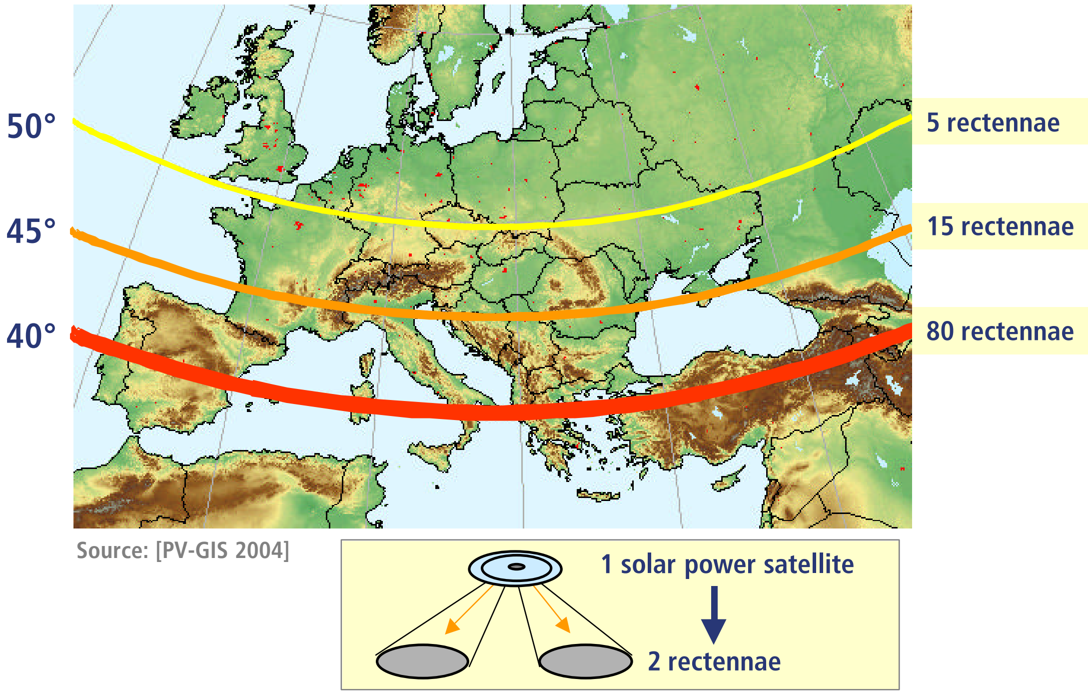


Figure 5-20: 500 GW scenario: siting of 100 rectennae along the 40°, 45° and 50° latitudes

5.2.3 Costs

Following assumptions for cost calculation for the SPS system are allocated for base load concepts (without launch and O&M costs):

Scenario	500 MW	5 GW	10 GW	50 GW	100 GW	500 GW
Number of space units	8	5	2	10	20	50
SSP System Manufacturing Capability						
Non-recurring costs	2640 M$	1680 M$	8050 M$	8050 M$	8050 M$	8050 M$
In space infrastructure						
Non-recurring costs	50 M$	50 M$	50 M$	50 M$	50 M$	50 M$
Cost per space segment unit	132 M$	382 M$	1909 M$	1184 M$	1184 M$	1909 M$
Space segment						
Unit nominal power level	250 MW	1 GW	5 GW	5 GW	5 GW	10 GW
Mass of a space segment unit	3534 t	12202 t	64453 t	64453 t	64453 t	133006 t
Equivalent diameter of transmitter	261 m	566 m	1265 m	1265 m	1265 m	1784 m
Energy storage system mass	-	-	-	-	-	-
AOCS propellant mass	100 t	500 t	3600 t	3600 t	3600 t	7500 t
Non-recurring costs	2030 M$	2467 M$	2467 M$	2467 M$	2467 M$	2499 M$
Unit hardware procurement	1044 M$	2332 M$	11515 M$	11515 M$	11515 M$	24770 M$
Ground segment						
Rectenna surface area (average)	2.93 km^2	9.86 km^2	49.31 km^2	50.44 km^2	50.44 km^2	50.81 km^2
Rectenna land area (average)	12.15 km^2	24.31 km^2	77.72 km^2	79.20 km^2	79.20 km^2	79.69 km^2
No of rectennae	2	5	2	10	20	100
Non-recurring costs	670 M$	1340 M$	3000 M$	3000 M$	3000 M$	4243 M$
Commercial power utilities systems						
Non-recurring costs	0	0	0	0	0	0
Average cost per unit	38 M$	150 M$	750 M$	750 M$	750 M$	750 M$

Table 5-6: Selected SPS systems for base load scenarios: technical data and investment costs

O&M costs are not considered in this calculation in accordance with the reference system [NASA 1997]. The influence of O&M costs regarding space transportation costs and energy effort could be significantly (e.g. [Charania 2000] assumed for an 1.2 GW Sun Tower that 5% of total SPS mass would need to be refurbished annually).

Launch costs are parameterized and not included in costs calculations. Further cost discussions regarding the launch effort is given in chapter 7.

Table 5-7 shows the cost split of SPS systems for different scenario sizes. Cost split structure and cost data inputs are based on the NASA Fresh Look Study [NASA 1997]. Cost calculations do not include costs for SPS launching (including 'B: Ground launch infrastructure', 'C: Earth to-orbit (ETO) system' and 'D: in space transportation'), 'T: Relay space segment' and deployment costs for all system components. See further details in the Report Annex A2.

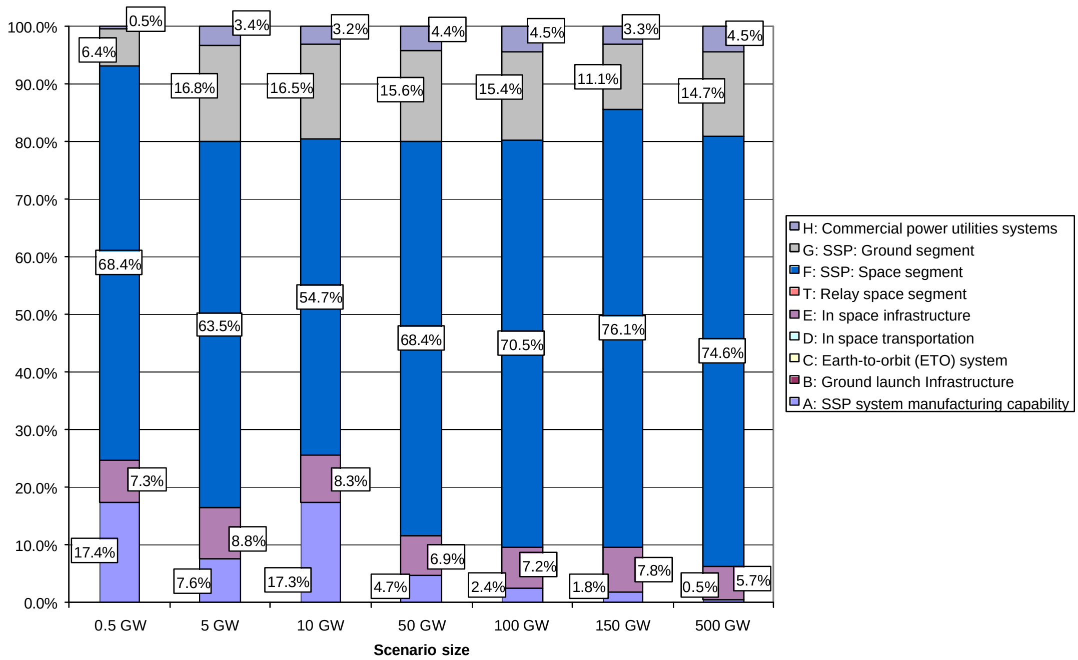


Table 5-7: Cost split of SPS systems for different scenario sizes. Launch costs are not includes.

As seen in Table 5-7 the major cost share of solar power satellite systems is the space segment (satellite) ranging from 54 % to 76 %. For 'Solar Disk' concepts the rectenna costs are between 11 to 17 % of the total investment costs. Rectenna cost of the 'Sun Tower' concept for 0.5 GW scenario is around 6 % of the total costs because of the installation of two 250 MW rectennae compared to eight 250 MW satellites in MEO.

COST SPLIT OF SPACE BASED CONCEPTS FOR BASE LOAD SCENARIOS

In the following the results of SPS systems with both storage options are shown in the diagrams. LECs do neither include launch nor O&M costs for SPS systems. Both diagrams show that the influence of electricity storage concept is marginal.

a) **Electricity storage via hydrogen**

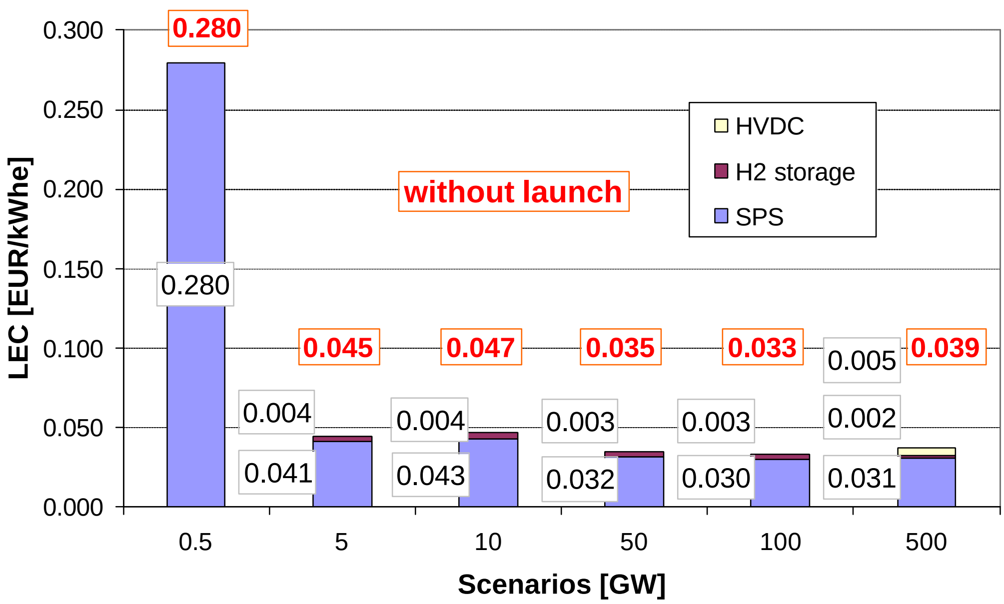


Figure 5-21: Split of LEC of space concepts for base load operation (including hydrogen storage) without launch

b) Electricity storage via pumped hydro

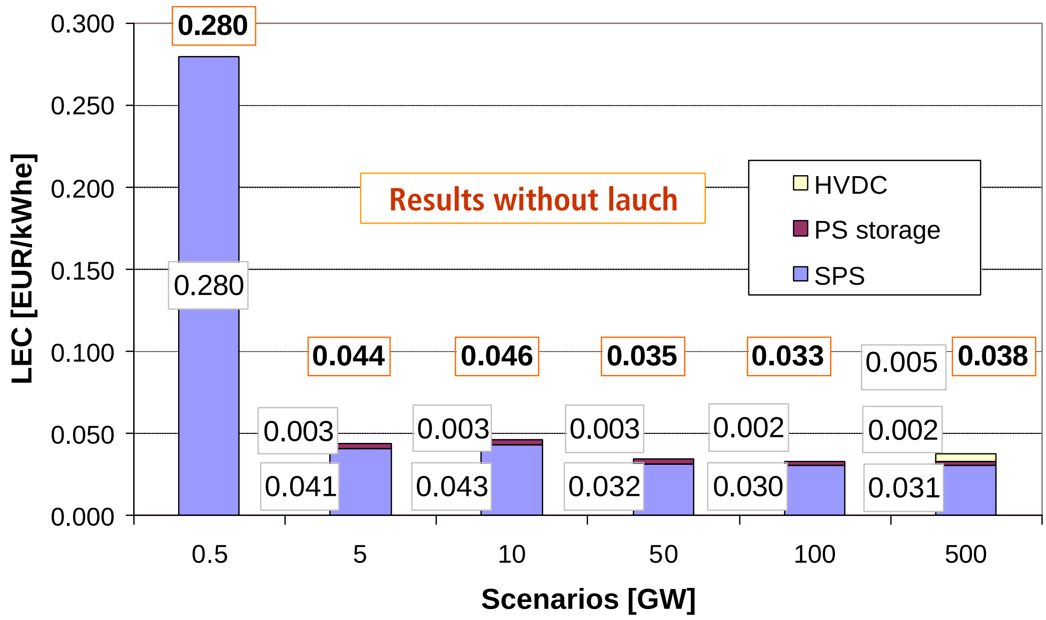


Figure 5-22: Split of LEC of space concepts for base load operation (including pumped hydro storage) without launch

c) Storage cost comparison

The diagram below compares the resulting costs of both selected electricity storage concepts for base load optimized SPS systems:

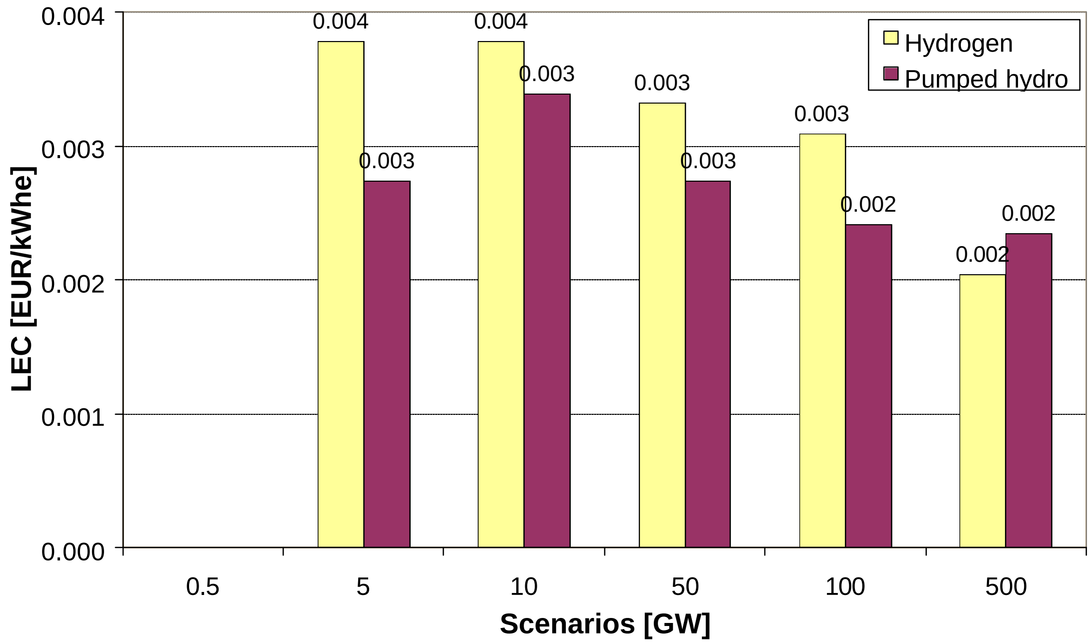


Figure 5-23: Comparison of LEC of electricity storage via H_2 and pumped hydro for SPS systems for base load scenarios

Further cost data are listed in the next chapter and compared with terrestrial concepts.

5.3 Cost comparison

5.3.1 Concepts

At the heart of this chapter is the comparison of levelised electricity costs (LEC) in terms of cent per kWh. However, even at an economic level, additional aspects must be included:

Technological maturity at different time scales

To reach the described specific energy cost has a long history for the individual technologies. This "pre-market period" requires different levels of financial commitment. In that respect it matters whether the money has to be spend for flexible technologies with low barriers to entrance, or whether the financial risk is very high by the time when guaranteed return of investment may be expected.

An analogue competition of various technologies at different levels of maturity can be observed even among the various technologies for terrestrial solar energy generation. E.g. PV costs today are much higher than SOT costs. Yet, PV shows a much faster market growth at present. Thus, PV costs are decreasing rapidly along the learning curve, and have fallen by nearly 2/3 over the last 15 years.

If SOT plants do not take off within the next 10 years or so, they possibly may never be competitive because the entrance cost barrier is relatively increasing. Costs for power generation from solar thermal power plants have been almost constant over the past 10 years due to the lack of a powerful market introduction concept.

This consideration holds to be true even more for SPS-based concepts.

Compatibility with electricity supply infrastructure

Another aspect, only marginally addressed in this study is the compatibility of the systems with present and future energy structures. For instance, the European Commission started a trend towards liberalization of energy markets in the last decade. In parallel technological developments towards the competitiveness of decentralized small scale power plant are making progress. These tendencies towards interwoven electrical networks more and more seem to favor small or medium scale investments for power plants. The advantage is the reduced technical risk in case of failure of any kind, but also the reduced financial risk for sudden changes of the market basics. As these conditions provide a tremendous high barrier for new large scale nuclear power plants in an liberalized energy market, they also will be so for large scale space based solar power plants, if these risks are not covered by somebody.

Environmental compatibility

The more human activities influence the global environment, the more their environmental compatibility has to be checked. In that respect a space based system might have advantages due to small land requirements. However, it must be ensured that other environmental interactions do not compensate for these advantages, such as interaction of launch exhaust gases with the atmosphere, interactions of the energy transmission with the environment etc.

Other effects

Some additional parameters to be addressed in a comparison might be the life cycle analysis concerning energy and resource consumption (see chapter 7), technical risk in case of failure (reliability), social acceptance, military risk in case of misuse of the transmitter, but also in case of supply interruptions due to sabotage (for all see chapter 10).

It is beyond the scope of this study to address all these topics. In this chapter the cost comparison with respect to specific electricity cost is performed. However, due to the broad range of uncertainty of the required launch efforts, this comparison is used to identify at which launch cost the SPS concept achieves electricity cost comparable to terrestrial solar energy supply. Furthermore, the calculated average launch cost is used to identify a learning curve for the launch. In other words, if the resulting cost decrease figures can be met with future launch vehicles, then SPS concepts could become a competitive electricity supply source in terms of costs.

In addition, in chapter 10 risks and reliabilities are discussed regarding the different technologies and their respective system architectures. Furthermore, in chapter 9 relevant parts of a life cycle analysis are presented. Primary energy and materials requirements are compared for the various scenarios. These two non-monetary parameters are equally relevant for the an overall assessment of terrestrial and space based power systems.

In the following chapter 5.3.2, the cost comparison is performed. The cost difference is calculated which can be filled with the launch in order to achieve competitive electricity cost between solar power satellites and terrestrial solar electricity production.

5.3.2 Costs

In the framework of scenario assumptions defined in the introduction to this chapter, Table 5-8 and Table 5-9 show the cost comparison of terrestrial and space-based concepts for base load scenarios' LEC in EUR/kWh_e.

The space-based solar power system is calculated without launch as well as without operation and maintenance (O&M) costs. O&M costs are not considered in the reference system in accordance with [NASA 1997]. The influence of O&M costs regarding space transportation costs and energy effort could be significantly (e.g. [Charania 2000] assumed for an 1.2 GW Sun Tower that 5% of total SPS mass would need to be refurbished annually).

The launch issue is discussed separately in chapter 7. This strategy was chosen as follows:

The total "allowable" launch cost are estimated from the comparison to calculate break even between terrestrial and SPS electricity cost. These "allowable" launch cost are reduced by the cost for the launch fuel, since the fuel certainly does not follow a technological cost digression pattern as the construction of the launch vehicle. It is unlikely that the cost of fuel will remain at current levels. Thus a tripling of natural gas costs is assumed for 2030 (see Report Annex A3 for further discussion). The resulting cost are translated into "allowable" launch vehicle cost per kg of payload. These average cost are compared with learning curves to identify that market introduction scenario, which results in acceptable electricity cost. In other words, that doubling period for 20% cost reduction has to be met to produce electricity at competitive prices.

The "allowable" launch cost are determined from:

$$\text{Limit for average } LEC_{launch} = LEC_{terrestrial\ systems} - LEC_{space\ systems\ (excl.\ launch)}$$

Depending on SPS mass which has to be transported to orbit the relevant data must be calculated for each scenario individually. These calculated cost limits for payload transportation are given in the tables below in $EUR/kg_{payload}$ for each scenario.

Further assessment of launch costs which are based on these cost limits in $EUR/kg_{payload}$ are discussed in chapter 7.

a) Electricity storage via hydrogen

Scenario [GW_e]	Concept	LEC without (electricity storage and HVDC) [EUR/kWh_e]	LEC electricity storage via H_2 [EUR/kWh_e]	LEC power transmission via HVDC [EUR/kWh_e]	**Total LEC [EUR/kWh_e]**
0.5	Terrestrial	0.064	0.026	0.000	**0.090**
	Space: Launch: 0 EUR/kg Launch: -- EUR/kg	0.280 --	0.000 --	0.000 --	**0.280** **--**
5	Terrestrial	0.054	0.026	0.000	**0.082**
	Space: Launch: 0 EUR/kg Launch 750 EUR/kg	0.041 0.079	0.003 0.003	0.000 0.000	**0.044** **0.082**
10	Terrestrial	0.054	0.026	0.000	**0.080**
	Space: Launch: 0 EUR/kg Launch: 620 EUR/kg	0.043 0.076	0.004 0.004	0.000 0.000	**0.047** **0.080**
50	Terrestrial	0.050	0.026	0.000	**0.076**
	Space: Launch: 0 EUR/kg Launch: 770 EUR/kg	0.032 0.073	0.003 0.003	0.000 0.000	**0.035** **0.076**
100	Terrestrial	0.049	0.026	0.000	**0.075**
	Space: Launch: 0 EUR/kg Launch: 770 EUR/kg	0.030 0.072	0.003 0.003	0.000 0.000	**0.034** **0.075**
500	Terrestrial	0.043	0.026	0.008	**0.076**
	Space: Launch: 0 EUR/kg Launch: 670 EUR/kg	0.031 0.068	0.003 0.003	0.005 0.005	**0.039** **0.076**

Table 5-8: Split of levelized LEC comparison of terrestrial and space concepts (electricity storage via H_2); In blue letters: Launch costs stated represent the break-even launch costs for each scenario; Total LEC may deviate due to rounding errors

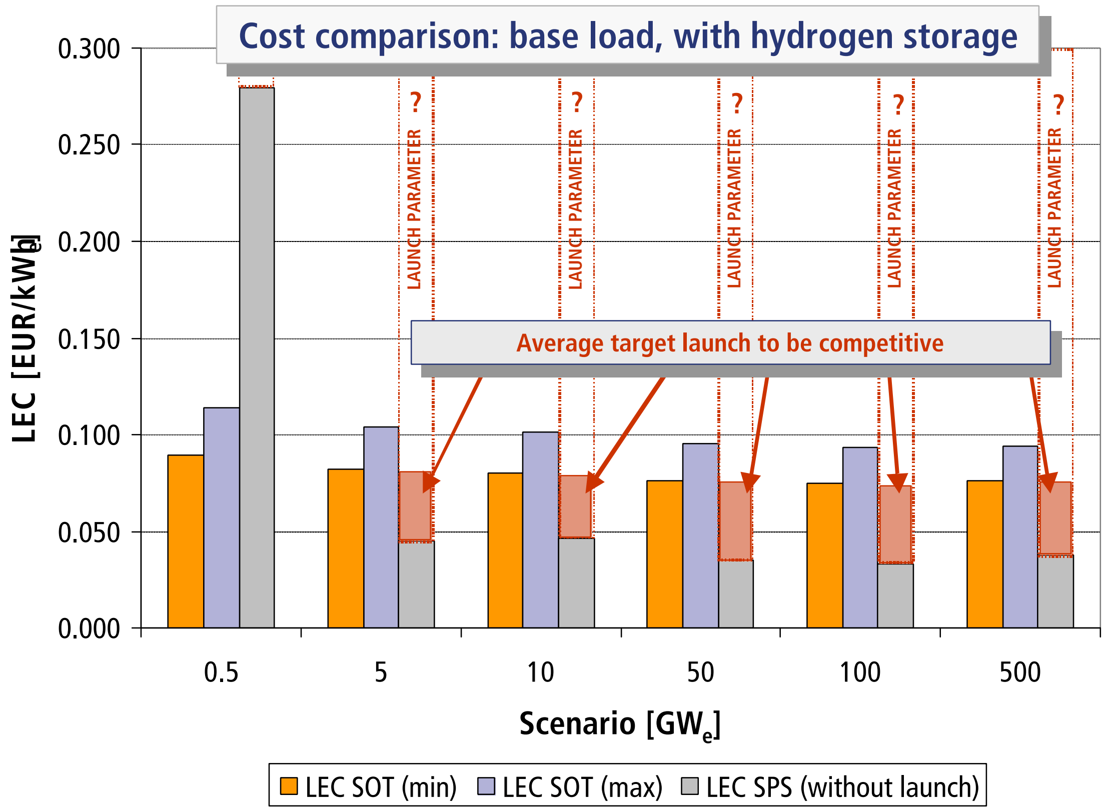


Figure 5-24: Cost comparison of terrestrial and space concepts (electricity storage via H_2)

b) Electricity storage via pumped hydro

Scenario [GW_e]	Concept	LEC without (electricity storage and HVDC) [EUR/kWh_e]	LEC electricity storage via pumped hydro storage [EUR/kWh_e]	LEC power transmission via HVDC [EUR/kWh_e]	**Total LEC [EUR/kWh_e]**
0.5	Terrestrial	0.046	0.013	0.000	**0.058**
	Space: Launch: 0 EUR/kg Launch: -- EUR/kg	0.280 --	0.000 --	0.000 --	**0.280** **--**
5	Terrestrial	0.040	0.013	0.000	**0.053**
	Space: Launch: 0 EUR/kg Launch: 200 EUR/kg	0.041 0.050	0.003 0.003	0.000 0.000	**0.044** **0.053**
10	Terrestrial	0.039	0.013	0.000	**0.0514**
	Space: Launch: 0 EUR/kg Launch: 90 EUR/kg	0.043 0.059	0.003 0.003	0.000 0.000	**0.046** **0.051**
50	Terrestrial	0.036	0.013	0.000	**0.049**
	Space: Launch: 0 EUR/kg Launch: 270 EUR/kg	0.032 0.046	0.003 0.003	0.000 0.000	**0.034** **0.049**
100	Terrestrial	0.035	0.013	0.000	**0.047**
	Space: Launch: 0 EUR/kg Launch: 250 EUR/kg	0.030 0.045	0.002 0.002	0.000 0.000	**0.033** **0.047**
500	Terrestrial	0.031	0.013	0.006	**0.050**
	Space: Launch: 0 EUR/kg Launch: 210 EUR/kg	0.031 0.043	0.002 0.002	0.005 0.005	**0.038** **0.050**

Table 5-9: Split cost comparison of terrestrial and space concepts (electricity storage via pumped hydro); In blue letters: Launch costs stated represent the break-even launch costs for each scenario; Total LEC may deviate due to rounding errors

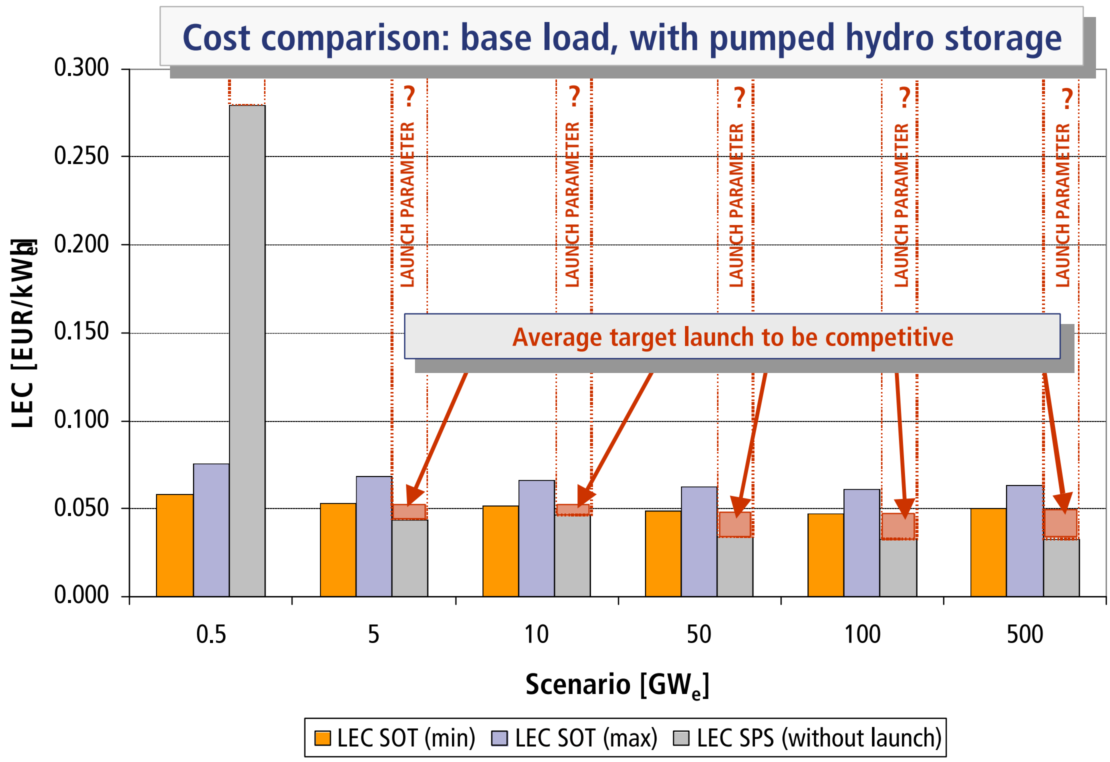


Figure 5-25: Cost comparison of terrestrial and space concepts (electricity storage via pumped hydro)

6 COMPARISON OF NON-BASE LOAD SCENARIOS (WP2)

For the purpose of this study, non-base load scenarios are defined as depicted in Figure 6-1. Thus, with increasing scenario sizes the plant utilization rises accordingly. This concept also comes closest to idea of "peak load" power production.

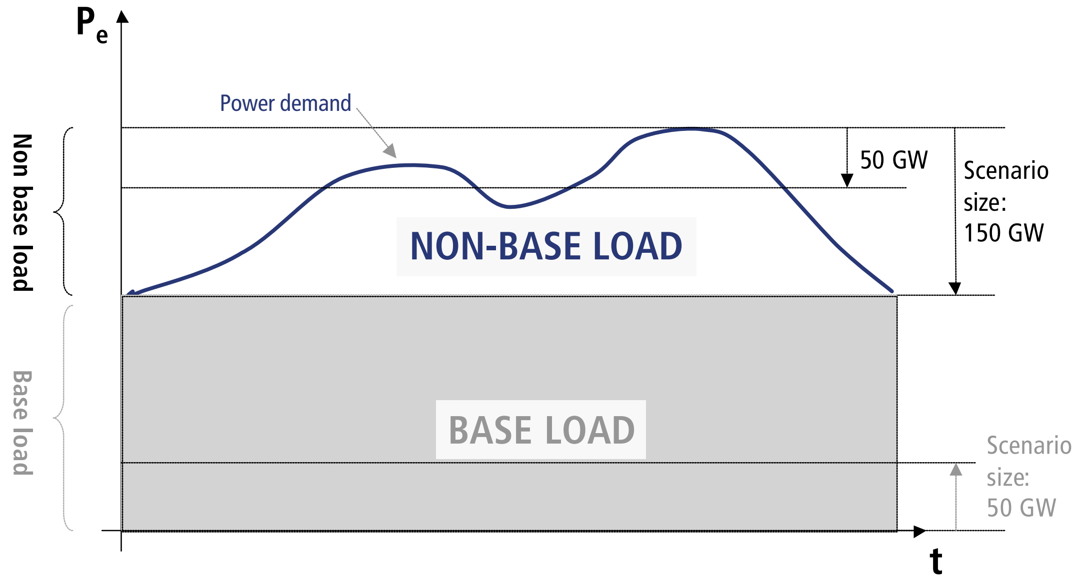


Figure 6-1: Definition of non-base load

As a result from Figure 6-1 non-base load scenarios have significantly lower equivalent full load hours compared to base load scenarios as depicted in Table 6-3.

Scenario	Full load hours
0.5 GW	5 h/yr
5 GW	9 h/yr
10 GW	18 h/yr
50 GW	288 h/yr
100 GW	989 h/yr
150 GW	1,730 h/yr

Table 6-1: Full load operation hours per year for non-base load scenarios

The maximum power level for non-base load scenarios is limited to 150 GW. Power levels beyond 150 GW are classified as non-base load power generation scheme which are discussed in the previous chapter 5.

6.1 Terrestrial concepts

6.1.1 Selected concept

The proposed concept for terrestrial non-base load PV applications consists of the integration of PV in buildings and facades (Figure 6-2)

Figure 6-2: Building integrated PV

as well as multiple usage of areas already consumed by civilization, e.g. PV-modules integrated in noise absorption (Figure 6-3), artificial roofing of highways for noise and pollution reduction etc.

Figure 6-3: PV integrated in noise absorption (left) and as roofing of a highway (right)

This kind of grid connected PV concept is well established in Western Europe. The fastest growing market is Germany, where installations of approximately 80 MW_p have been achieved in 2003. Other already existing markets in Europe are the Netherlands and Switzerland. Arising markets are to be found in Spain, Italy and France.

The concept of building integration of PV has several advantages:

1. No extra land use, multiple usage of areas to share costs is possible.

2. Proximity to the customer and investor allows project financing by private investors.

Terrestrial PV concepts underly basic assumptions defined at the first ESTEC workshop (Table 6-2).

	TODAY	2030
Efficiency mono-crystalline module	14%	21%
Learning curve start costs for poly and mono crystalline systems	4,500 EUR/kW_p	
Learning curve factor	20%	

Table 6-2: Basic PV system definitions for terrestrial applications

a) Centralized power plants versus building integrated PV

Building integrated PV power is the power production the closest possible to the customer. The benchmark for PV-produced power costs therefor is not the power production cost at the power plant, but rather the customer end price. This end price is likely to be at 0.06-0.16 €/kWh, which is twice the sales price at the power plant (0.03-0.08 €/W). This is due to the distribution chain from power plant to customer as shown in.

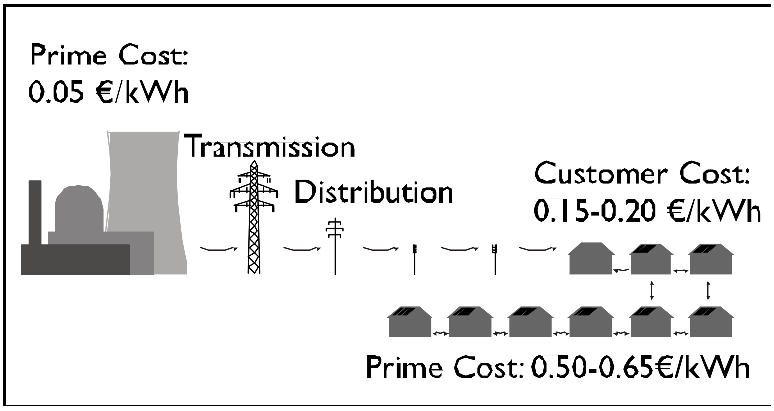


Figure 6-4: Prime cost vs customer cost; transmission and distribution make the electrical power costs double for customers

b) No storage or peak shaving needed for a market share below 20%

As long as PV produced electrical power has a market share of 20% or less, it can be used directly by the customer or fed into the existing low voltage grid (3 phases, 400 V). This saves costly storage and the necessity of building new high voltage power transmission lines. If the PV power market share exceeds 20%, considerations about power transmission and storage become necessary again.

c) The European sunbelt versus Germany

Today the German market has the biggest share in PV activity in Europe, responsible for about 80% of the total PV power sold in Europe. This is due to the Renewable Energy Sources Act ("Erneuerbare-Energien-Gesetz"). For photovoltaics the compensation just has been changed at the beginning of 2004. The compensation guaranteed by this law is at least 45.7 Eurocent per kWh in 2004. For PV plants with a capacity below 30 kW_p which are installed on roofs or on a noise barrier the compensation is 57.4 Eurocent per kWh [EEG 2003].

The proposed PV applications in the European Sunbelt would generate similar installations as seen in Germany in the target countries Portugal, Spain, Italy, Greece and Turkey. Compared to a southward looking PV installation in Germany, solar radiation in the European Sunbelt is at about 130-160% of the received solar radiation in Germany.

If it is possible to produce similar installations for a similar price, this would have a very positive effect on the costs of PV power. In addition to the higher radiation level a large population of PV grid connected installations in the same market will also allow to apply economy of learning to local crafts man as well as economy of volume. This leads to a great decrease in BOS costs, as observed in the German market. The decrease of BOS costs will take place at the same time as the decrease of the module price due to the learning curve.

Typical installations are in the range of 20 kWp to 100 kW_p. They can be installed on larger industrial buildings, noise absorption walls or along highways. On a smaller scale, such installations can also be built on houses, with a typical capacity of 2 – 6 kW_p.

d) Lifecycle cost consideration

The proven lifecycle of PV modules is beyond twenty years. For the inverter it is between ten and twelve years. This means a standard installation needs two inverters within the life time of the same modules. Inverters only take a share of 6-8% in system costs, so they can be easily replaced in existing installations. The new inverter will now not only be available at a lower price but will also have a better performance ratio as the replaced one.

The costs for insurance and the operating and maintenance costs including overhauling (e.g. replacement of the DC/AC inverter after 10 to 12 years) are indicated with in total about 1.5% of the investment of the PV plant.

e) Grid

In contrast to the base load solar thermal power stations no high voltage direct current (HVDC) transmission lines are required because all PV installations are within Europe. The PV plants are distributed on the roofs of buildings.

6.1.2 Costs

a) PV peak load scenario with H_2 storage

For the calculation of the share of the electricity which has been supplied via hydrogen the hourly demand over the year has been compared with the hourly supply of PV electricity. The required electricity can be directly derived from the PV plant only when the electricity generated by the PV plants overlaps with the electricity demand at the same time. Table 6-3 shows the layout for the different peak load scenarios.

	0.5 GW	5 GW	10 GW	50 GW	100 GW	150 GW
Capacity FC plant [GW]	0.5	5	10	50	100	150
Capacity PV modules [GW]	0.007	0.126	0.519	37	210	587
Number of loading/unloading cycles	1	1	1	10	20	50
Share of direct PV electricity	0%	0%	0%	18%	32%	36%
Electricity demand [GWh/a]	2.5	42.8	176.5	14,416.3	89,767	259,544
thereof supplied directly from PV [GWh/a]	0	0	0	2,595	28,725	93,436
thereof supplied via H_2 [GWh/a]	2.5	42.8	176.5	11,821	61,042	166,108

Table 6-3: Layout of the different peak load scenarios employing H_2 storage

In case of the 0.5 GW, 5 GW and 10 GW peak load scenarios all electricity has to be generated via the hydrogen pathway because the peak load only occurs at a few hours per year and mainly in winter. No electricity can be derived from the PV plant directly. With higher PV capacity (50 GW, 100 GW, 150 GW scenarios) the amount of electricity directly derived from the PV plant increases because the "peak load" moves towards "medium load" and partly overlap with the electricity demand within the European electricity grid.

The investment for the electrolysis plant have been assumed to be 500 EUR per kW of hydrogen output. The investment for the fuel cell power plant has been assumed to be 500 EUR per kW_e. The hydrogen storage consists of spherical pressure vessels (approximately 1.9 million EUR per unit). The average investment for the PV plant depends on the cumulative installed capacity. Table 6-4 shows the investment for the different peak load scenarios.

	0.5 GW	5 GW	10 GW	50 GW	100 GW	150 GW
PV plant	44	744	2,957	122,084	513,446	1,236,459
Electrolysis plant	2	41	169	12,181	68,135	190,626
H_2 storage	59	1,008	4,156	27,840	71,879	78,240
FC power plant	250	2,500	5,000	25,000	50,000	75,000
Total	**355**	**4,293**	**12,282**	**187,105**	**703,460**	**1,580,325**

Table 6-4: Investment for different peak load scenarios employing H_2 storage [million EUR]

Table 6-5 shows the annual costs for the different scenarios.

	0.5 GW	5 GW	10 GW	50 GW	100 GW	150 GW
Capital costs	25.79	311.9	892.3	13,593	51,106	114,809
O&M PV plant	0.66	11.16	44.4	1,831	7,702	18,547
O&M electrolysis	0.03	0.6	2.5	183	1022	2859
O&M FC plant	0.03	0.4	1.8	118	610	1661
Total	**26.51**	**324.1**	**940.9**	**15,725**	**60,440**	**137,876**

Table 6-5: Annual costs for different peak load scenarios employing H_2 storage [million EUR/yr]

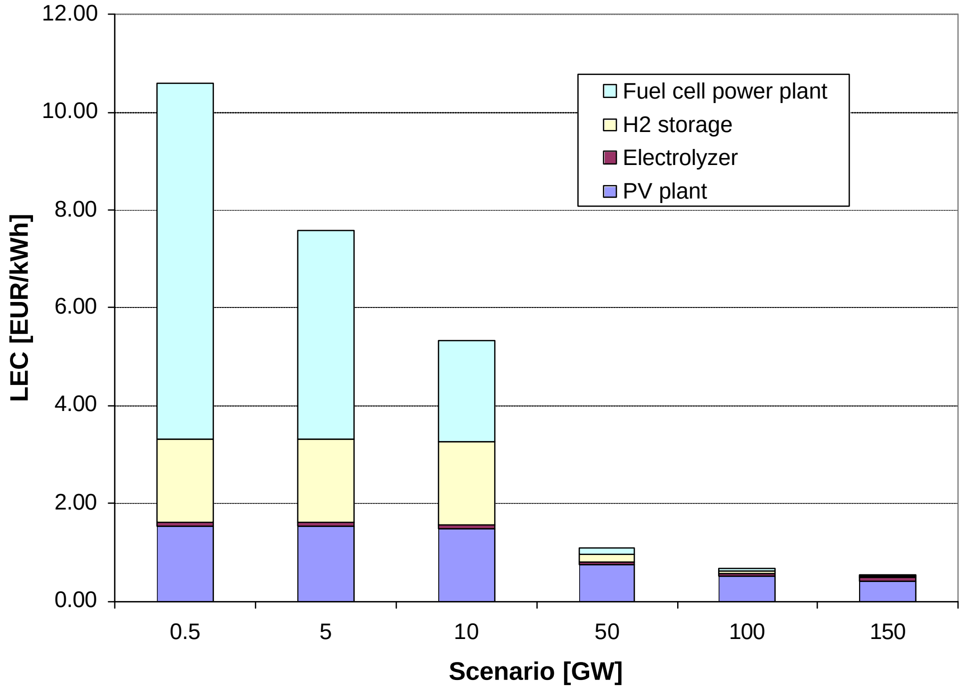


Figure 6-5: Split of costs of electricity supply for the different scenarios with H_2 storage

b) PV peak load scenario with pumped hydro

If pumped hydro is used for electricity storage the required PV capacity will decrease because of the higher efficiency. The lower PV capacity reduces the amount of electricity directly produced by the PV plant (less overlapping of direct PV electricity supply and peak electricity demand).

	0.5 GW	5 GW	10 GW	50 GW	100 GW	150 GW
Capacity PV modules [GW]	0.003	0.053	0.218	17.6	107	306
Number of loading/unloading cycles	1	1	1	10	20	50
Share of direct PV electricity	0%	0%	0%	10%	22%	30%
Electricity demand [GWh/a]	2.5	42.8	176.5	14,416.3	89,767.0	259,544
thereof supplied directly from PV [GWh/a]	0	0	0	1,442	19,749	77,863
thereof supplied via pumped hydro [GWh/a]	2.5	42.8	176.5	12,975	70,018	181,681

Table 6-6: Layout of the different peak load scenarios employing pumped hydro storage

Table 6-7 shows the investment and Table 6-8 the annual costs for the different non-base load scenarios employing pumped hydro for electricity storage.

	0.5 GW	5 GW	10 GW	50 GW	100 GW	150 GW
PV plant	18	315	1,278	65,368	292,352	708,825
Pumped hydro	330	3,514	8,118	45,570	102,011	133,603
Total	348	3,829	9,396	110,938	394,363	842,428

Table 6-7: Investment for different non-base load scenarios employing pumped hydro storage [million EUR]

	0.5 GW	5 GW	10 GW	50 GW	100 GW	150 GW
Capital costs	25.28	278.15	683	8,059	28,650	61,202
O&M PV plant	0.27	4.73	19	981	4,385	10,632
O&M pumped hydro	0.01	0.17	1	52	280	727
Total	**25.56**	**283.05**	**702**	**9,092**	**33,315**	**72,561**

Table 6-8: Annual costs for different non-base load scenarios employing pumped hydro storage [million EUR/yr]

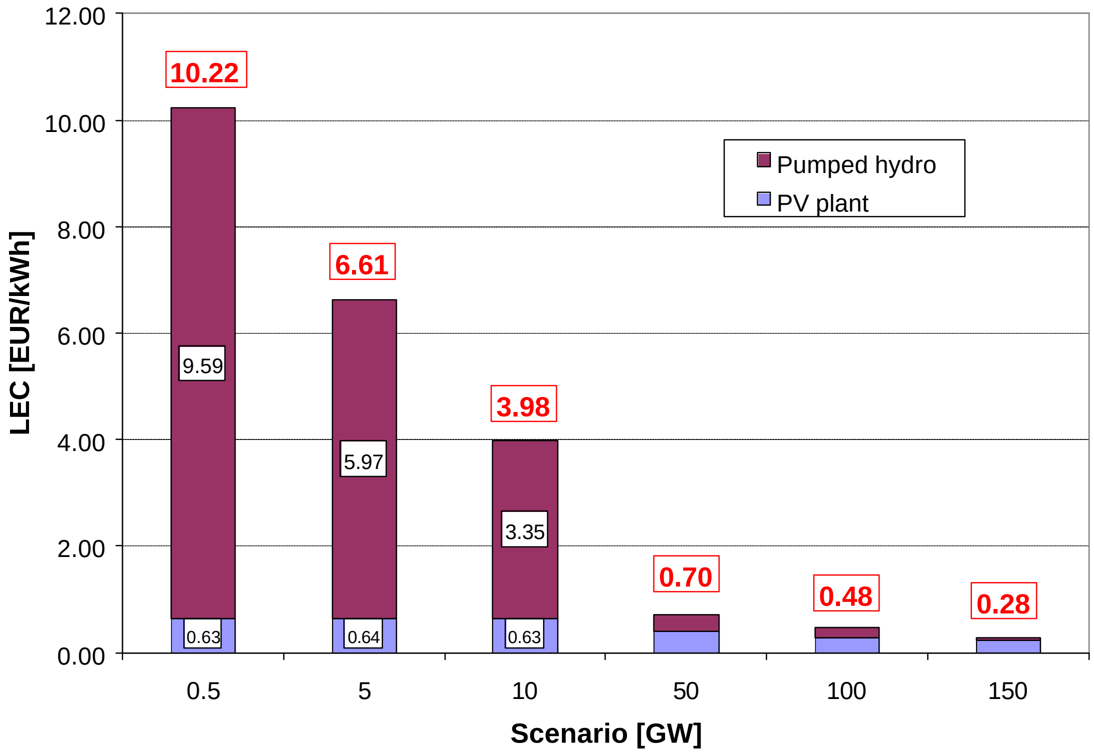


Figure 6-6: Split of costs of electricity supply for the different non-base load scenarios applying pumped hydro storage

c) Storage cost comparison

Figure 6-7 shows a comparison of the electricity costs for the different scenarios employing hydrogen storage and pumped hydro storage.

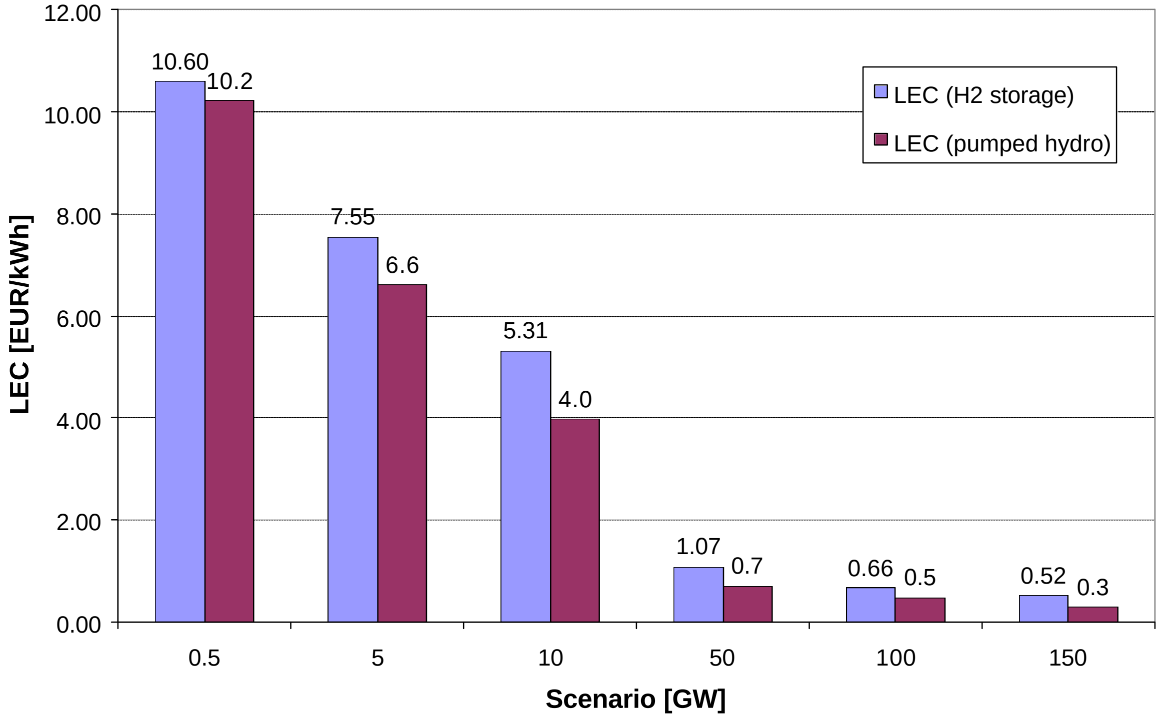


Figure 6-7: Levelized electricity costs (LEC) of terrestrial concepts for non-base load scenarios

The use of pumped hydro storage leads to lower electricity costs than the use of hydrogen for electricity storage. Yet, it has to be noted that pumped hydro power plants are subject to favorable environmental conditions. The modularity in terms of plant size provides another advantage of hydrogen storage over pumped hydro storage.

6.2 Space concepts

6.2.1 Selected concept

For non-base load scenarios the same technical space concepts are selected as for base load scenarios (see technical description of SPS systems in previous chapter 5.2).

Compared to base load scenarios SPS systems opterated for non-base load operation achieve signifcantly lower load factors, see Figure 6-1.

In the following the results of SPS systems with both storage options are shown in the diagrams. The LECs stated in Figure 6-8 and Figure 6-9 do neither include launch nor

O&M costs for SPS systems. Both diagrams show that the influence of the electricity storage is marginal for either concept. The influence of O&M costs is potentially significant (e.g. [Charania 2000] assumed for an 1.2 GW Sun Tower that 5% of total SPS mass would need to be refurbished annually).

a) Electricity storage via hydrogen

The cost split of Figure 6-8 shows the negligible influence of both the hydrogen storage and electricity power transmission (HVDC) requirements for the overall power generation costs of SPS.

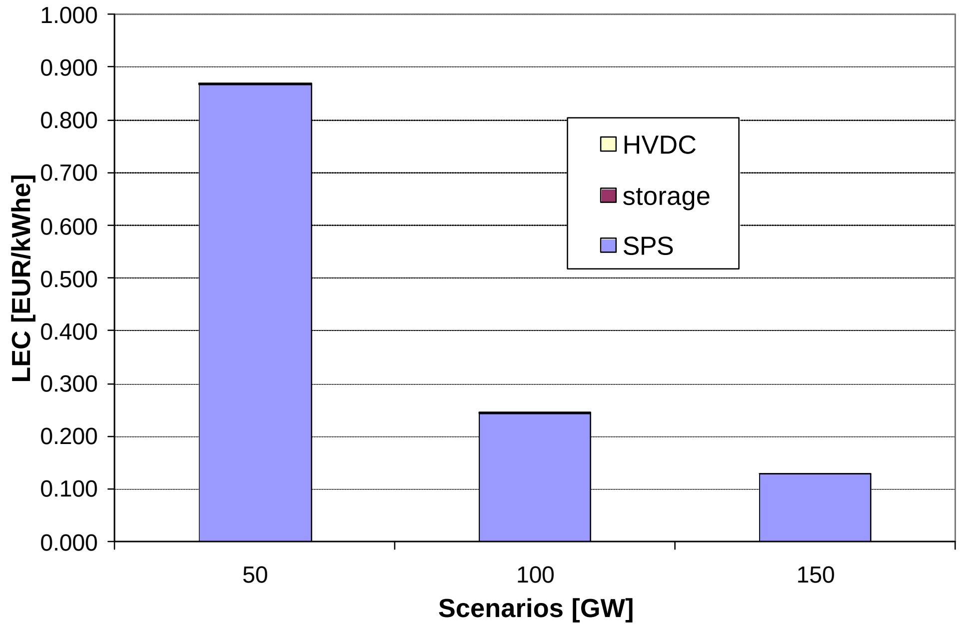


Figure 6-8: Split of LEC of space concepts for non-base load operation without launch

b) Electricity storage via pumped hydro

The cost split of Figure 6-9 shows the negligible influence of both the pumped hydro storage and electricity power transmission (HVDC) requirements for the overall power generation costs of SPS.

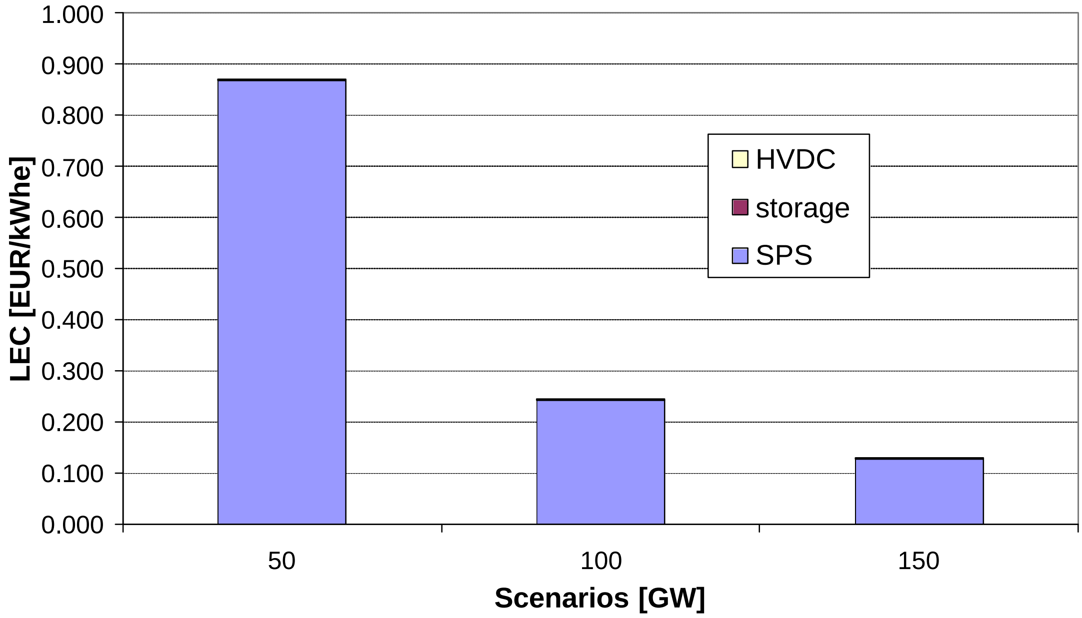


Figure 6-9: Split of LEC of space concepts for non-base load operation excluding launch costs

Further cost data are listed in the next chapter and compared with terrestrial concepts.

6.3 Cost comparison

In accordance with chapter 5.3 "Cost comparison" such a concept comparison has many facets which have to be considered even by a pure cost comparison.

In the following, the focus is put on a cost comparison. This is done in the same way as in chapter 5.3. The cost difference is calculated which can be filled with the launch in order to achieve competitive electricity cost between solar power satellites and terrestrial solar electricity production.

In addition, in chapter 10 risks and reliabilities are discussed regarding the different technologies and their respective system architectures. Furthermore, in chapter 9 relevant parts of a life cycle analysis are presented. Primary energy and materials requirements are compared for the various scenarios. These non-monetary parameters are equally relevant for the evaluation of terrestrial and space based power systems.

Table 6-9/Table 6-10 and Figure 6-10/Figure 6-11 show the cost comparison of terrestrial with space based concepts for non-base load scenarios' LEC in EUR/kWh$_e$ with hydrogen storage and pumped hydro storage respectively.

Analogue to the preceding chapter 5, the space-based solar power system is calculated without launch as well as without operation and maintenance (O&M) costs. O&M costs are not considered in the reference system in accordance with [NASA 1997]. The influence of O&M costs regarding space transportation costs and energy effort could be significantly (e.g. [Charania 2000] assumed in their 1.2 GW Sun Tower concept that 5% of total SPS mass would need to be refurbished annually).

The launch cost is used as free parameter to calculate the appropriate learning curves which would eventually result in competitive electricity cost. In this chapter the "allowable" cost for the launch are extracted from the comparison of terrestrial and space power generation costs (the latter excluding launch cost), i.e. representing the maximum allowable average cost for launch as shown in Equation 6-1.

$$LEC_{launching} = LEC_{terrestrial\ systems} - LEC_{space\ systems\ (excl.\ launch)}$$

Equation 6-1: Calculation of allowable average cost for space transportation for space-based solar power systems in order to become competitive with terrestrial solar power systems under the scenario conditions given in this study

The average cost figures derived from Equation 6-1 are used in chapter 7 to calculate a proposed learning curve for the launch vehicles. The fuel cost have to be considered separately as these cost do not decline with increasing flight frequency.

Depending on SPS mass which has to be transported to orbit in each scenario concept and the full load hours of operation cost limits for payload transportation are evaluated. These resulting cost limits for payload transportation are given in the tables below in $EUR/kg_{payload}$ for each scenario.

Further assessment of launching costs which base on these cost limits in $EUR/kg_{payload}$ are discussed in more detail in chapter 7.

a) Electricity storage via hydrogen

Scenario [GW_e]	Concept	LEC without electricity storage and HVDC [EUR/kWh_e]	LEC electricity storage via H_2 [EUR/kWh_e]	LEC power transmission via HVDC [EUR/kWh_e]	**Total LEC [EUR/kWh_e]**
0.5	Terrestrial	1.54	9.06	0.000	**10.6**
	Space: Launch: 0 EUR/kg Launch: -- EUR/kg	441 --	0.000 --	0.000 --	**441** **--**
5	Terrestrial	1.52	6.05	0.000	**7.6**
	Space: Launch: 0 EUR/kg Launch: -- EUR/kg	36 --	0.003 --	0.000 --	**36** **--**
10	Terrestrial	1.47	3.86	0.000	**5.3**
	Space: Launch: 0 EUR/kg Launch: -- EUR/kg	19 --	0.004 --	0.000 --	**19** **--**
50	Terrestrial	0.742	0.349	0.000	**1.090**
	Space: Launch: 0 EUR/kg Launch: 155 EUR/kg	0.868 1.087	0.003 0.003	0.000 0.000	**0.871** **1.090**
100	Terrestrial	0.501	0.172	0.000	**0.673**
	Space: Launch: 0 EUR/kg Launch: 985 EUR/kg	0.243 0.670	0.003 0.003	0.000 0.000	**0.246** **0.673**
150	Terrestrial	0.418	0.114	0.000	**0.532**
	Space: Launch: 0 EUR/kg Launch: 1615 EUR/kg	0.128 0.529	0.003 0.003	0.000 0.000	**0.131** **0.532**

Table 6-9: Split of levelized electricity costs (LEC) and comparison of terrestrial and space concepts (electricity storage via hydrogen)

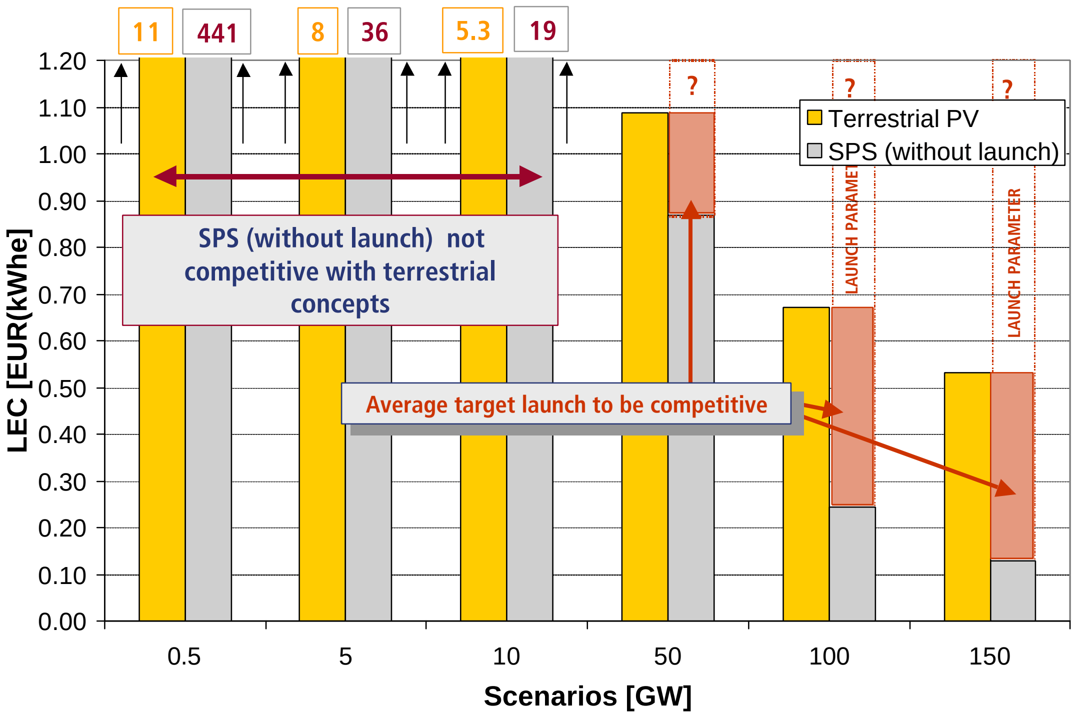


Figure 6-10: Cost comparison of terrestrial and space concepts (without O&M as well as launch costs) with electricity storage via H_2

b) Electricity storage via pumped hydro

Scenario [GW_e]	Concept	LEC without electricity storage and HVDC [EUR/kWh_e]	LEC electricity storage via pumped hydro [EUR/kWh_e]	LEC power transmission via HVDC [EUR/kWh_e]	**Total LEC [EUR/kWh_e]**
0.5	Terrestrial	0.631	9.594	0.000	**10.2**
	Space: Launch: 0 EUR/kg Launch -- EUR/kg	441 --	0.000 --	0.000 --	**441** **--**
5	Terrestrial	0.645	5.967	0.000	**6.6**
	Space: Launch: 0 EUR/kg Launch -- EUR/kg	36 --	0.003 --	0.000 --	**36** **--**
10	Terrestrial	0.635	3.346	0.000	**4.0**
	Space: Launch: 0 EUR/kg Launch -- EUR/kg	19 --	0.003 --	0.000 --	**19** **--**
50	Terrestrial	0.397	0.303	0.000	**0.700**
	Space: Launch: 0 EUR/kg Launch -- EUR/kg	0.868 --	0.003 --	0.000 --	**0.871** **--**
100	Terrestrial	0.285	0.190	0.000	**0.480**
	Space: Launch: 0 EUR/kg Launch 540 EUR/kg	0.243 0.478	0.002 0.002	0.000 0.000	**0.245** **0.480**
150	Terrestrial	0.239	0.040	0.000	**0.280**
	Space: Launch: 0 EUR/kg Launch 605 EUR/kg	0.128 0.278	0.002 0.002	0.000 0.000	**0.130** **0.280**

Table 6-10: Split of levelized electricity costs (LEC) and comparison of terrestrial and space concepts (electricity storage via pumped hydro storage)

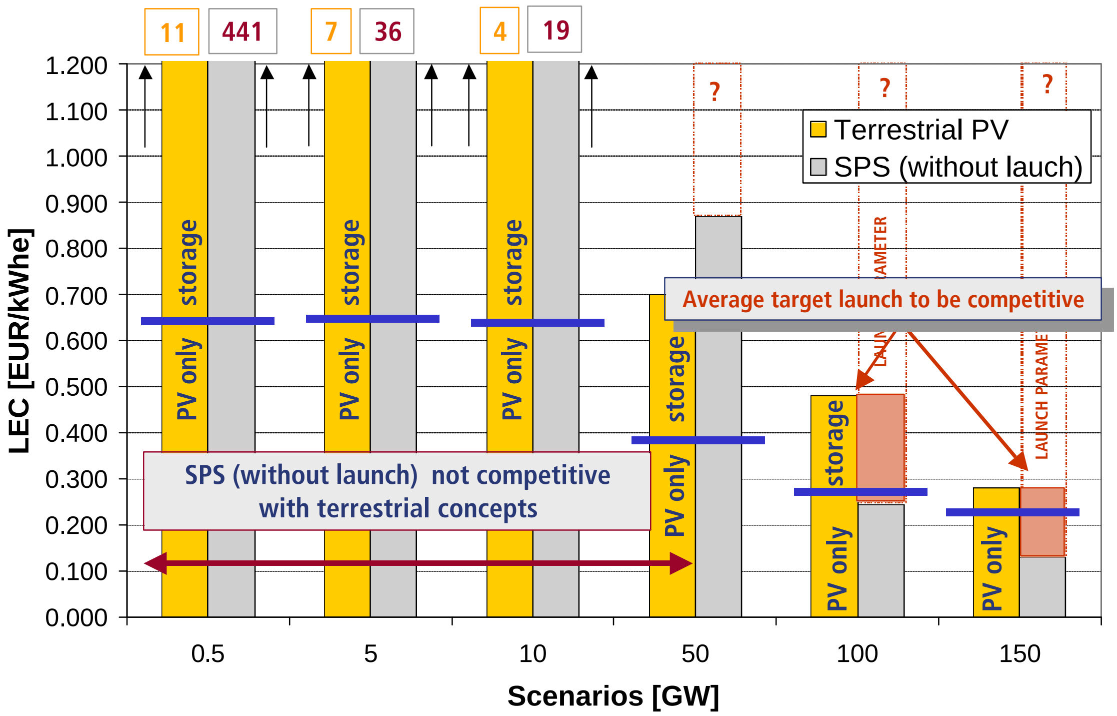


Figure 6-11: Cost comparison of terrestrial and space concepts (without O&M as well as launch costs) with electricity storage via pumped hydro

Figure 6-11 shows also the cost splits for terrestrial PV plants: PV system and storage cost share.

7 LAUNCH

Among other topics, the overall viability of space-based solar power system concepts strongly depends on the technical and commercial viability of space transportation. As agreed by both consortia and the ESA Advanced Concepts Team, the cost of space transportation is implemented by means of a parametric approach. In the course of this chapter, a multi-stage approach is chosen as following to derive the average target cost of space transportation ("launch"):

1. Definition of basic launch assumptions (chapter 7.1).

2. Definition of target costs for space transportation (chapter 7.2).

3. Development of synthetic learning curves for launch vehicles in a way that they may become competitive (chapter 7.3).

It is beyond the scope of this study to discuss technological progress, launch vehicle concepts etc. This chapter solely focuses 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.

7.1 Basic assumptions

For the determination of the required learning curve for SPS launching following assumptions on input parameters are allocated:

a) Launch vehicle

– Payload transport capacity today: 100 tons per year

– Payload transport costs today: 10,000 EUR/$kg_{payload}$

– Maximum cumulated SPS mass to be launched until 2030:

Scenario size	SPS mass to orbit
0.5 GW	28,272 t
5 GW	61,010 t
10 GW	128,906 t
50 GW	644,530 t
100 GW	1,289,060 t
150 GW	1,933,590 t
500 GW	6,650,590 t

Table 7-1: Mass to orbit transportation demand according to the scenario size

– Learning effect: according to joint agreement at the first ESTEC workshop, each doubling of mass transport capacity reduces the payload transport cost by 20%

c) Fuel

For the discussion of fuel cost share and the influence on launch costs in chapter 7.3 following data are assumed:

– fuel consumption: 71 kg_{fuel} / $kg_{payload}$ [5]

– fuel costs for launch: €0.4/kg_{fuel} (today) – €0.9/kg_{fuel} (2030) [6]

See detailed derivation of cost of launch fuel in the Report Annex A3.

7.2 Cost targets

From the comparison in chapter 5 and 6 the average cost figures for the launch were extracted which must be met in order to achieve cost competitiveness of solar power satellites with terrestrial solar power plants. Table 7-2 shows the average launch cost targets for SPS to become competitive with terrestrial solar electricity depending on the specific energy storage concept and basing on the scenarios defined in the framework of this study.

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5 [NASA 1997, p. 86]: useable propellant mass = 804,530 kg; payload capability (nominal)= 11,343 kg

6 Tripling of natural gas price, see more in the Report Annex A3.

Scenario size	Hydrogen storage	Pumped hydro storage
Base load 0.5 GW	not competitive	not competitive
Base load 5 GW	750 $EUR/kg_{payload}$	200 $EUR/kg_{payload}$
Base load 10 GW	620 $EUR/kg_{payload}$	90 $EUR/kg_{payload}$
Base load 50 GW	770 $EUR/kg_{payload}$	270 $EUR/kg_{payload}$
Base load 100 GW	770 $EUR/kg_{payload}$	250 $EUR/kg_{payload}$
Base load 500 GW	670 $EUR/kg_{payload}$	210 $EUR/kg_{payload}$
Non-base load 0.5 GW	not competitive	not competitive
Non-base load 5 GW	not competitive	not competitive
Non-base load 10 GW	not competitive	not competitive
Non-base load 50 GW	155 $EUR/kg_{payload}$	not competitive
Non-base load 100 GW	985 $EUR/kg_{payload}$	540 $EUR/kg_{payload}$
Non-base load 150 GW	1615 $EUR/kg_{payload}$	605 $EUR/kg_{payload}$

Table 7-2: Resulting average launch cost targets for SPS systems for base load and non-base load scenarios.

7.3 Derivation of learning curve

7.3.1 Method of calculation

The calculated average launch cost targets in Table 7-2 still include the contribution for the propellant. However, the fuel cost do not follow a learning pattern. The dominating cost share is the primary energy effort – in the case of LH_2 natural gas. Furthermore, liquefaction of hydrogen and air are established technologies with long industrial experience. Some room of efficiency improvement exist (e.g. $< 0.3\ kWh_e/kWh_{LH2}$). However, any improvement would eventually be overcompensated due to fossil fuel resource constraints which will result in a cost increase over time. As discussed in the Report Annex A3, fuel costs will likely remain within a price band of $\$0.4/kg_{fuel}$ - $\$0.9/kg_{fuel}$. For the year 2030 the upper $\$0.9/kg_{fuel}$ are chosen. The $\$0.9/kg_{fuel}$ translate into $\$64/kg_{payload}$. This would be in the range of fuel production from renewable sources which adds certainty to these cost calculations. The resulting average launch cost target is shown in Figure 7-1 for pumped hydro storage and Figure 7-2 for hydrogen storage.

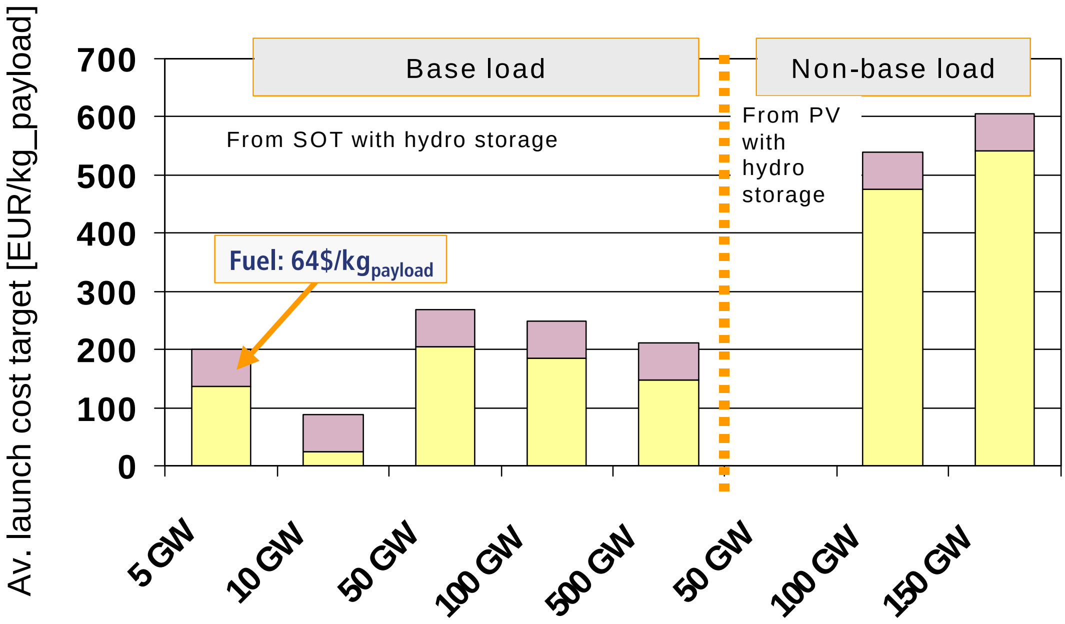

Figure 7-1 Average launch cost target for SPS in order to become competitive with terrestrial solar electricity production including pumped hydro storage according to the scenarios defined in this study

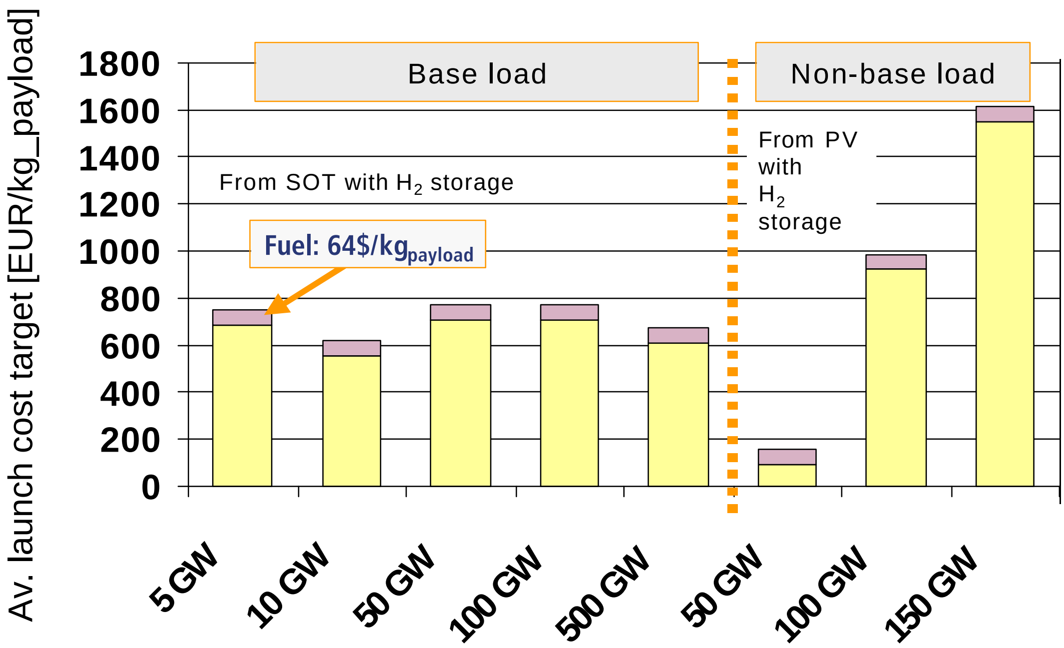

Figure 7-2 Average launch cost target for SPS in order to become competitive with terrestrial solar electricity production including hydrogen storage according to the scenarios defined in this study

For each scenario the status of learning along the curve is different according to the different production volumes. This results in different specific electricity cost for the various scenarios, and, finally, in different average fuel cost to become competitive. In most of the scenarios the share of fuel cost is minimal.

For the non-base load scenarios below 50 GW no cost target could be identified for the solar satellites. Even with zero cost for launch and propellant, these concepts lead to considerably higher costs than terrestrial systems. However, this is not surprising since solar power satellite systems are surely not designed for power generation at very low equivalent full load hours.

These average target costs still must be translated into the learning curves for the different scenarios.

For this learning curve a 20% cost reduction with each doubling of launch capacity is assumed. Formally, this correlation may be stated according to Equation 7-1.

$$c(p) = c_0 \cdot 0.8^{\log_2\left(\frac{p}{p_0}\right)}$$

Equation 7-1: Learning curve – launch capacity vs costs

with

c_0 = launch cost per kg payload at capacity p_0 ,

p_0= initial launch capacity with cost c_0 , this parameter is used as free parameter

p = cumulative payload in the target period,

c(p)= launch cost per kg payload at target cumulative capacity p.

The cumulative launch cost (c_{cum}) is derived by integration according to Equation 7-2.

$$c_{cum} = \int_{p_0}^{p_{scenario}} c(p) \cdot dp = \frac{c_0 \cdot p_0}{\frac{\ln(0.8)}{\ln(2)} + 1} \cdot \left[\left(\frac{p_{scenario}}{p_0} \right)^{\frac{\ln(0.8)}{\ln(2)}+1} - 1 \right]$$

Equation 7-2: Cumulative launch cost

with

$p_{scenario}$ = total mass of all solar power satellites with scenario power output.

The free parameter, p_0 , is varied to match the average cost target according to the following equation:

$$c_{average} \cdot p_{scenario} = c_{cum}$$

with

$c_{average}$ = target average launch cost per kg payload as derived from Figure 7-1

Since today the launch frequency is so low that its cost cannot be connected with something like an industrial cost learning curve, this parameter p_0 might be interpreted as the cumulated capacity at which an initial 20% cost reduction must be achieved to become competitive. After $2p_0$ a 36% cost reduction must be achieved, after $4p_0$ a 49% cost reduction, and so forth. Once industrial production sets in these curves can be used to check whether the target can be met or is beyond being met without additional drivers for cost reduction.

Other choices could be to fix the initial launch volume and to vary either the learning effect or the initial cost until the cost target is met.

The calculation method is also visualized with the following Figure 7-3.

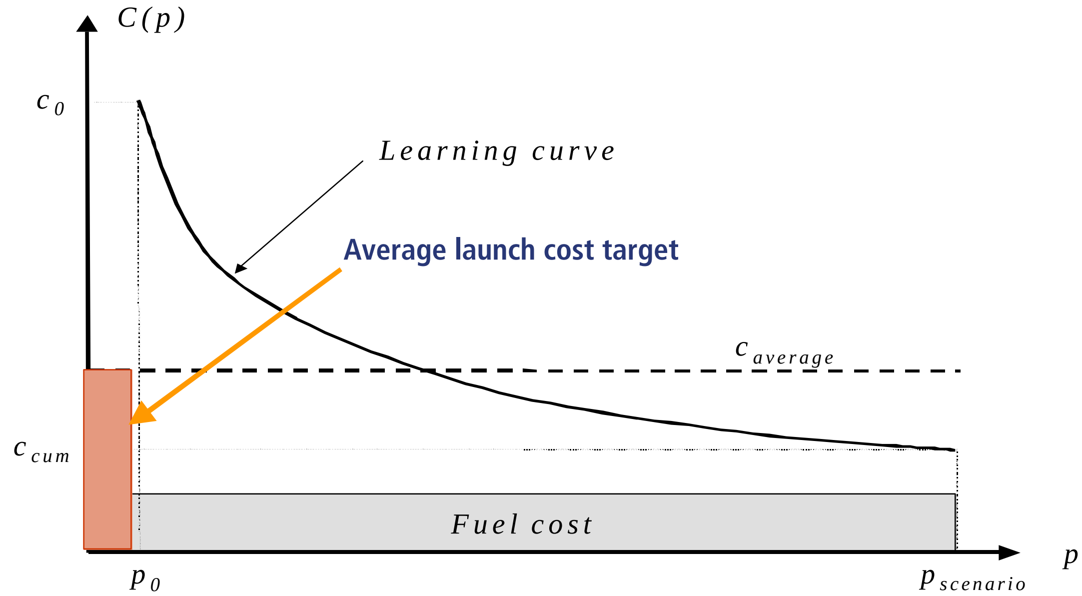

Figure 7-3: The learning curve has to meet the average target cost

7.3.2 Results

Table 7-3, Table 7-4, Table 7-5 and Table 7-6 show the specific data for the required learning curves for all SPS systems with the final cost target c_{cum} for each scenario. The tables include:

– the average cost targets $c_{average}$, calculated for base load and non-base load scenarios,

– the specific SPS mass $p_{scenario}$ which has be transported into space for each scenario,

– the required initial mass transportation capacity per year p_0 depending on the initial launch payload transportation cost c_o, to fulfil the requirements of the learning curve for launch cost reduction: today's transport costs c_o are assumed to start with 10,000 EUR/$kg_{payload.}$ The tables show also the initial required mass capacities for lower initial launch costs starting with c_o = 7,500 EUR/$kg_{payload}$ and c_o= 5,000 EUR/$kg_{payload}$, see Figure 7-4,

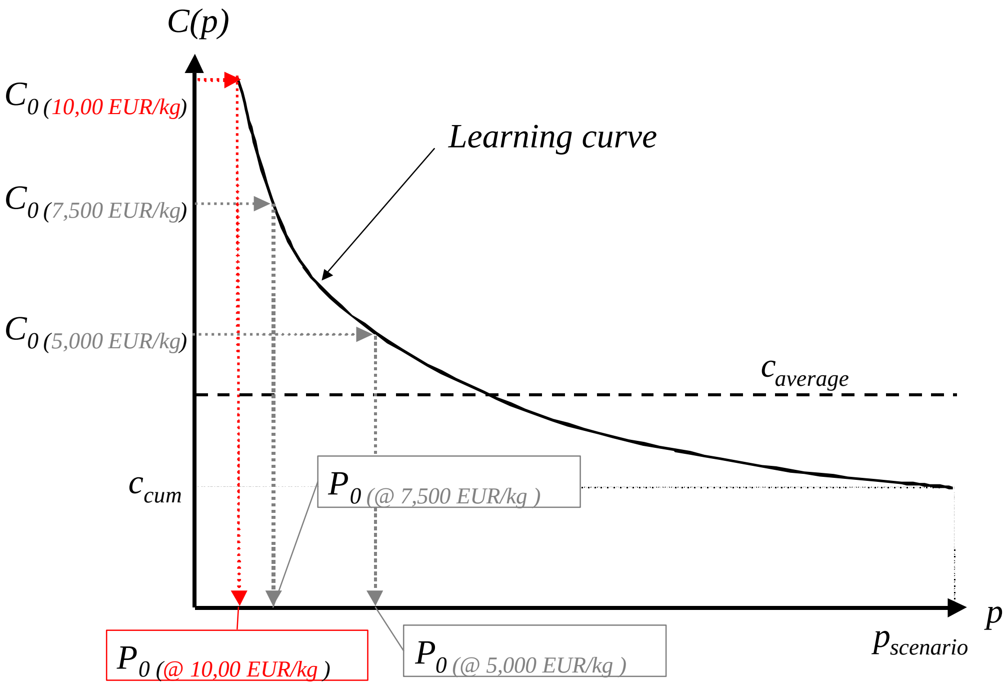

Figure 7-4: Different initial mass transportation capacities p_o are required for different initial costs c_o to reach calculated learning curve.

– and the final cost targets c_{cum} which have to be achieved for each scenario. The main SPS mass has to be transported at these cost targets into space.

a) Base load scenarios

In the following, the results of these calculations are presented for base load (chapter 5) with pumped hydro storage. The following diagrams show the specific cost targets for launch depending on the different scenarios. For the total specific launch cost, the fuel with 64 $EUR/kg_{payload}$ must be added (based on 0.9 EUR/kg_{fuel}). A lower limit based on today's gas prices could be set at 28 EUR/kg.

Base load scenario Pumped hydro	Average target $c_{average}$ [EUR/kg]	SPS mass $p_{scenario}$ [1000t]	Initial doubling p_0 at 10 kEUR/kg [t]	Initial doubling p_0 at 7.5 kEUR/kg [t]	Initial doubling p_0 at 5 kEUR/kg [t]	Final cost c_{cum} [EUR/kg]
5 GW	136	61	0.029	0.07	0.25	92
10 GW	26	128.8	0.00035	0.087	0.003	17
50 GW	206	644.5	1.12	2.7	9.6	140
100 GW	186	1.29 mio	1.6	4	14	125
500 GW	146	6.65 mio	4	9.7	34	99

Table 7-3: Relevant parameters for launch cost learning curve to achieve target cost for pumped hydro storage for the base load scenarios

Summarizing these results lead to the conclusion, that total specific launch cost

- of between 81EUR/kg and 206 EUR/kg (including propellant) must be achieved at the end of each scenario time scale, and
- the doubling period ranges from below 1 kg payload capacity to 4 tons payload capacity at initial cost of 10,000 EUR/kg.

From the current perspective, these targets seem to be quite unrealistic without the introduction of new reusable vehicle technology.

In the following, the results of these calculations are presented for the base load scenario with hydrogen storage. The following tables show the specific cost targets for launch depending on the different scenarios. For the total specific launch cost, the fuel with 64 EUR/$kg_{payload}$ must be added (based on 0.9 EUR/kg_{fuel}).

Base load scenario H2	Average target $c_{average}$ [EUR/kg]	SPS mass $p_{scenario}$ [1000t]	Initial doubling p_0 at 10 kEUR/kg [t]	Initial doubling p_0 at 7.5 kEUR/kg [t]	Initial doubling p_0 at 5 kEUR/kg [t]	Final cost c_{cum} [EUR/kg]
5 GW	686	61	4.45	10.8	39	466
10 GW	556	128.8	4.9	12	42,5	378
50 GW	706	644.5	51,3	126	450	480
100 GW	706	1.29 mio	100	240	865	480
500 GW	606	6.65 mio	330	809	2875	411

Table 7-4: Relevant parameters for launch cost learning curve to achieve target cost for hydrogen storage for the base load scenarios

Summarizing these results lead to the conclusion, that total specific launch cost

- of between 442 EUR/kg and 546 EUR/kg (including propellant) must be achieved at the end of each scenario's time scale, and
- The doubling period ranges from below 14.5 tons payload capacity to 330 tons payload capacity at initial cost of 10,000 EUR/kg depending on the scenario sizes.

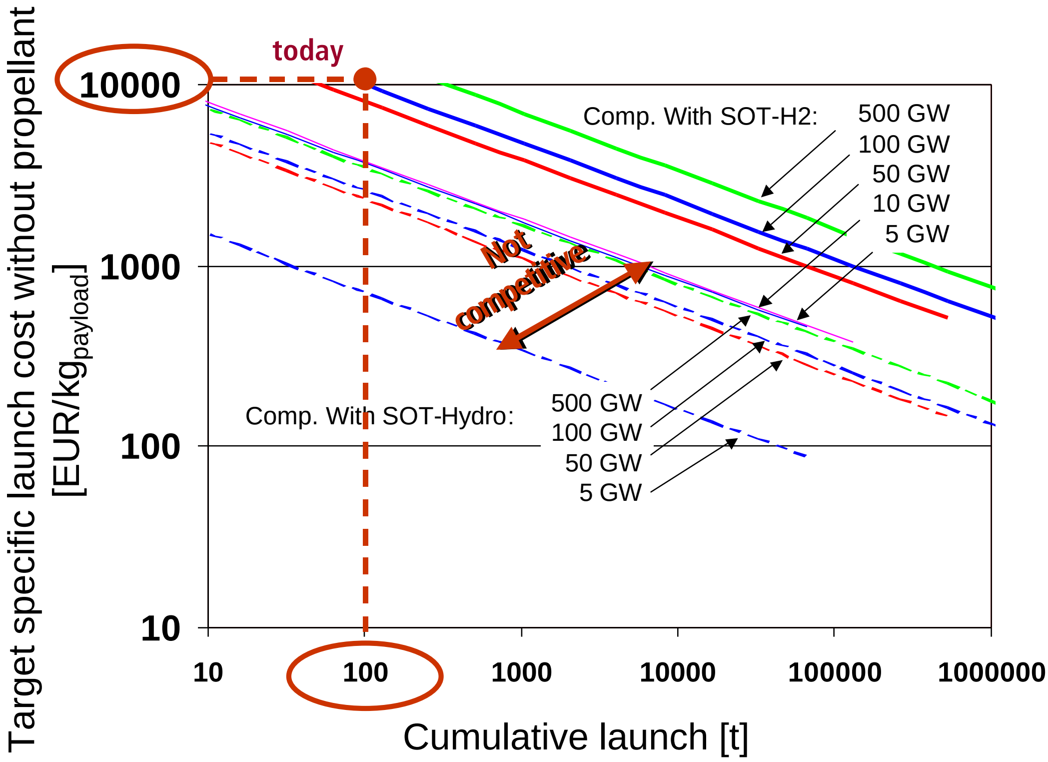

Figure 7-5: Calculated target learning curves for the launch cost (without propellant) in order to become cost competitive with the terrestrial base load scenarios based on pumped hydro storage and hydrogen storage respectively

b) Non-base load

In the following, the results of these calculations are presented for non-base load (chapter 6) with pumped hydro storage. The following diagrams show the specific cost targets for launch depending on the different scenarios. Scenarios below a scenario size of 100 GW are more expensive than terrestrial non-base load scenarios even without cost for launch vehicle and launch energy. For the total specific launch cost, the fuel with \$64/kg$_{payload}$ must be added (based on \$0.9/kg$_{fuel}$).

Non-base load scenario H2	Average target $c_{average}$ [EUR/kg]	SPS mass $p_{scenario}$ [1000t]	Initial doubling p_0 at 10 kEUR/kg [t]	Initial doubling p_0 at 7.5 kEUR/kg [t]	Initial doubling p_0 at 5 kEUR/kg [t]	Final cost c_{cum} [EUR/kg]
100 GW	476	1.29 mio	30	74	260	323
150 GW	541	6.65 mio	230	570	2000	366

Table 7-5: Relevant parameters for launch cost learning curve to achieve target cost for pumped hydro storage for non-base load scenarios

Summarizing these results lead to the conclusion, that total specific launch cost

- of between \$387/kg and \$430/kg (including propellant) must be achieved at the end of each scenario time scale, and
- the doubling period ranges from 30 tons payload capacity to 230 tons payload capacity at initial cost of 10,000 EUR/kg.

In the following, the results of these calculations are presented for non-base load (chapter 6) with hydrogen storage. The following diagrams show the specific cost targets for launch depending on the different scenarios. Smaller sizes then 50 GW are more expensive than terrestrial peak load scenarios even without cost for launch vehicle and launch energy. For the total specific launch cost, the fuel with \$64/$kg_{payload}$ must be added (based on \$0.9/kg_{fuel}).

Non-base load scenario H2	Average target $c_{average}$ [EUR/kg]	SPS mass $p_{scenario}$ [1000t]	Initial doubling p_0 at 10 kEUR/kg [t]	Initial doubling p_0 at 7.5 kEUR/kg [t]	Initial doubling p_0 at 5 kEUR/kg [t]	Final cost c_{cum} [EUR/kg]
50 GW	91	644.5	0.087	0.2	0.76	62
100 GW	921	1.29 mio	235	580	2,095	625
500 GW	1551	6.65 mio	6,250	15,700	60,000	1060

Table 7-6: Relevant Parameters for launch cost learning curve to achieve target cost for hydrogen storage for non-base load scenarios

Summarizing these results lead to the conclusion, that total specific launch cost

- of between \$126/kg and \$1,134/kg (including propellant) must be achieved at the end of each scenario time scale, and
- The doubling period ranges from 3,090 kg payload capacity to 1,200 tons payload capacity at initial cost of 10,000 EUR/kg.

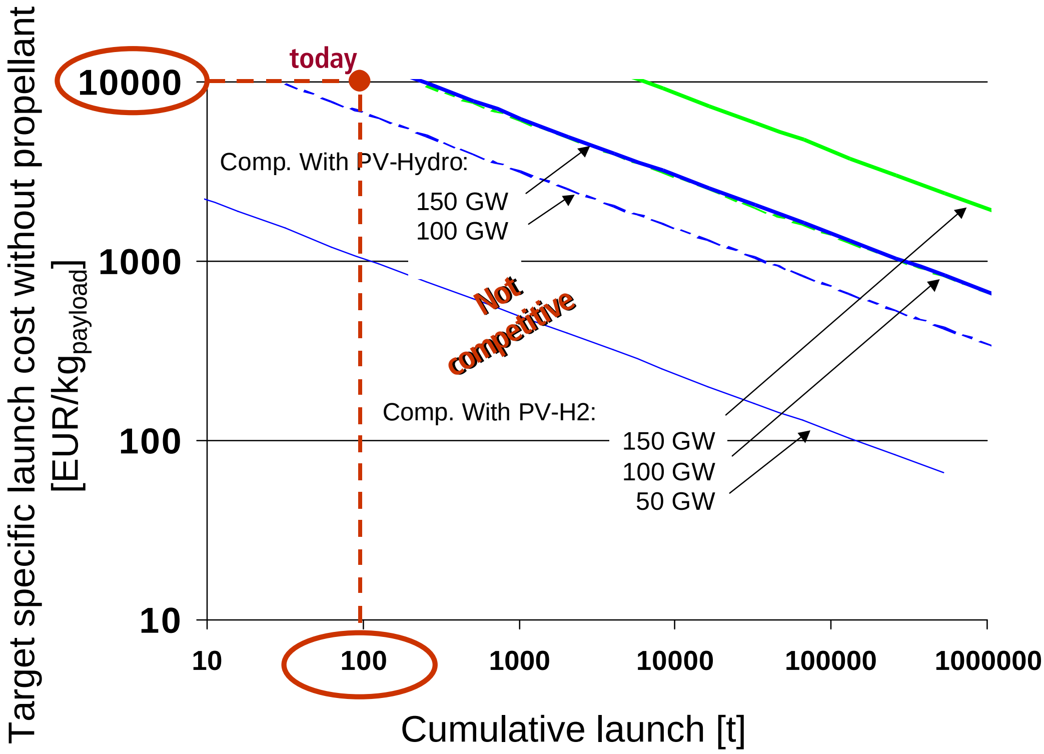

Figure 7-6: Calculated target learning curves for the launch cost (without propellant) in order to become cost competitive with the terrestrial solar non-base load solutions based on pumped hydro storage and on hydrogen storage

8 SYSTEM COMBINATION (WP3)

In the course of this chapter possible synergies between terrestrial and space power systems are discussed.

Mutual synergies by means of concept combination could not be identified.

Potential synergies resulting from the combination of terrestrial and space-based solar power systems can be found yet with unbalanced benefits for both systems. These synergies are discussed in Section 8.1 from the terrestrial and in Section 8.2 from the space perspective. Further potential synergies could be found in fields which are beyond the scope of this study. These are discussed in Section 8.3.

8.1 Space and terrestrial synergies from the terrestrial perspective

In the following subchapters, the two most promising technological synergies for the terrestrial solar power plant development and operation are described and discussed.

8.1.1 Synergies in the production of space and terrestrial solar cells

The mass manufacturing of photovoltaic (PV) cells for solar space systems as it is assumed in WP1 and WP2 scenarios may offer for terrestrial PV systems the chance for cost reductions due to positive effects in the course of PV manufacturing.

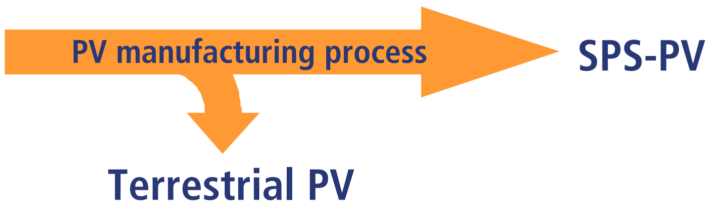

Figure 8-1: Evaluation of potential synergies during PV manufacturing process for space and terrestrial system

As a result of WP1 and WP2 as well as the discussion on launch (see chapter 5 'Comparison of base load scenarios', chapter 6 'Comparison of non-base load scenarios' and chapter 7 'Launch') none of the SPS concepts for WP1 and WP2 scenarios is competitive to terrestrial solar power plants below an installed SPS power capacity of 50 GW for base load and 100 GW for non-base load scenarios. If thus focusing on large-scale scenarios, large PV manufacturing capacities have to be considered regarding a potential SPS mass production for further synergy scenario discussions and evaluations.

The mass manufacturing of large quantities of PV cells, modules and finally systems for SPS could lead to further process innovations. For the commercial production of SPS-PV cells in the multi-GW range, e.g. advanced respectively new thin film production technologies have to be put into practice. Such significant process progresses initiated by SPS-PV manufacturers could also boost the manufacturing process of PV systems for terrestrial applications and may thus accelerate the commercialization of low cost terrestrial PV systems. Figure 8-2 illustrates that innovations during the PV manufacturing process – such as the development of advanced thin film coating technologies – could lead to a technology transfer from 'SPS-PV factories' to 'terrestrial PV-factories'.

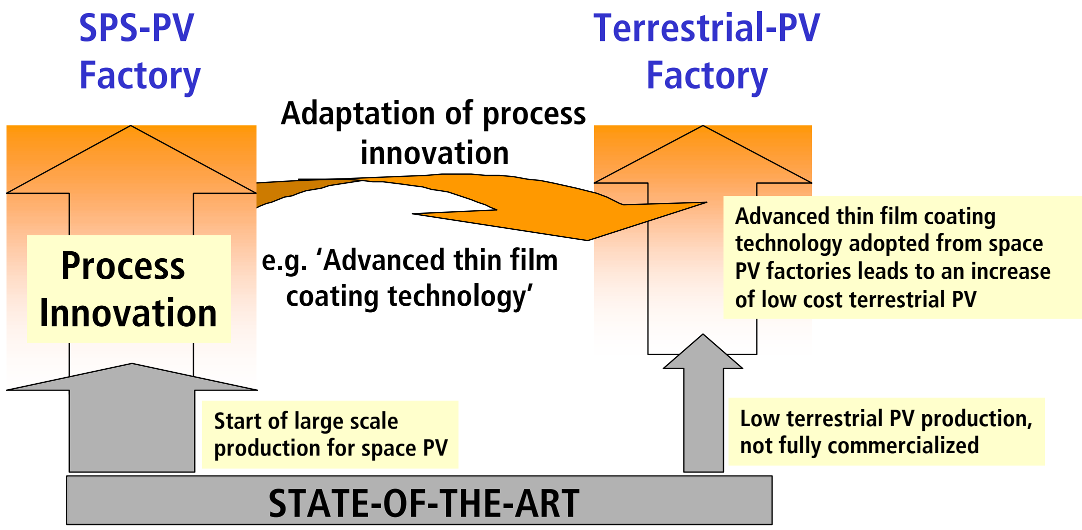

Figure 8-2: Synergies during PV production: process innovations implemented by PV manufacturers for SPS applications could be adopted by PV manufacturers for terrestrial systems, e.g. advanced thin film coating technology

A further major positive effect due to synergies in the mass manufacturing of PV for SPS is given for silicon based PV cells. Silicon based PV cells offer high potentials of synergies during early production stages. The main difference in the production of Si based terrestrial and space solar generators is their encapsulation [IMT 2004b]. Figure 8-3 illustrates the major manufacturing process steps of PV cells for both applications.

One of the most important steps to PV mass production on a multi-GW scale is the substitution of so-called 'electronic-grade silicon' (EGS) by 'solar-grade silicon' (SGS). EGS is a preliminary product of the electronics industry (semiconductor production), where silicon is required with a very high purity. Today's Si-cell production solely relies on EGS as waste product. Yet, for '2030 scenarios' large amounts of silicon are required which will by far exceed today's resource basis of EGS. As EGS would be too expensive to be exclusively produced for the Si-PV industry, 'solar-grade silicon' will have to be used which is optimized for PV use. The build-up of a SGS supply industry would thus support the establishment of a new resource basis for terrestrial Si-based PV cells, too.

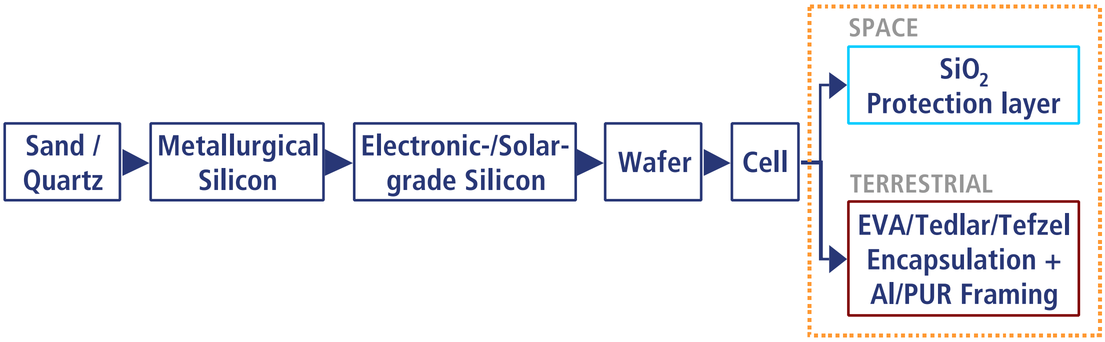

Figure 8-3: Similar technological process steps for the production of PV cells for space and terrestrial systems offers potential cost reductions due to synergies during the manufacturing process

In a joint resource basis / production of solar cells, the annual output of PV is higher compared to divided technology development pathways. This would result in a faster-than-usual progress of cost reductions of which the terrestrial market would benefit directly. Due to the longer lead time of space based solar power systems, the terrestrial market may well run ahead of the space market development. The terrestrial PV market development may finally disturb the target market of space-based solar power systems. The market situation is depicted in Figure 8-4.

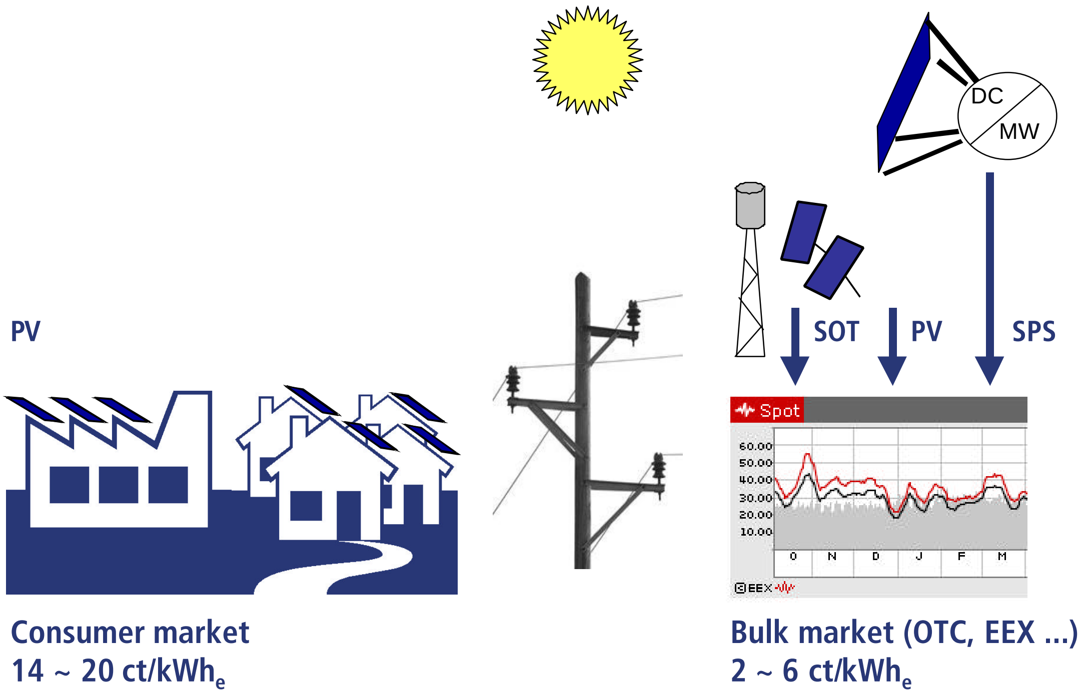

Figure 8-4: Electricity markets and current prices

8.1.2 Substitution of terrestrial energy storage needs

In this subchapter the additionally required electricity storage capacities – which were required by the terrestrial solar thermal (SOT) power plants for 'WP1 base load scenarios' as well as from the terrestrial photovoltaic (PV) power plants for 'WP2 non-base load scenarios' – these storage capacities may be substituted by solar power satellite (SPS) power systems. Chapter a) discusses this synergy from a terrestrial perspective for base load scenarios whereas chapter 6.3b) focuses on non-base load scenarios.

a) Base load scenarios

Analog to the scenarios described in chapter 'WP1 base load' further terrestrial concepts with SOT but also with PV systems are regarded in operational combination with SPS systems and evaluated for the corresponding base load power levels of 0.5 GW / 5 GW / 10 GW / 50 GW / 100 GW and 500 GW. Thereby terrestrial SOT systems supply power for 6,400 equivalent full load hours per year and terrestrial PV systems achieve 1,335 equivalent full load hours per year. The lack of 2,360 h/yr (which is equal to 8,760 h/yr – 6,400 h/yr) for SOT and 7,425 h/yr (equal to 8,760 h/yr – 1,335 h/yr) for PV scenarios to achieve the required base load operation time of 8,760 h/yr are supplied by SPS systems (see Figure 8-5).

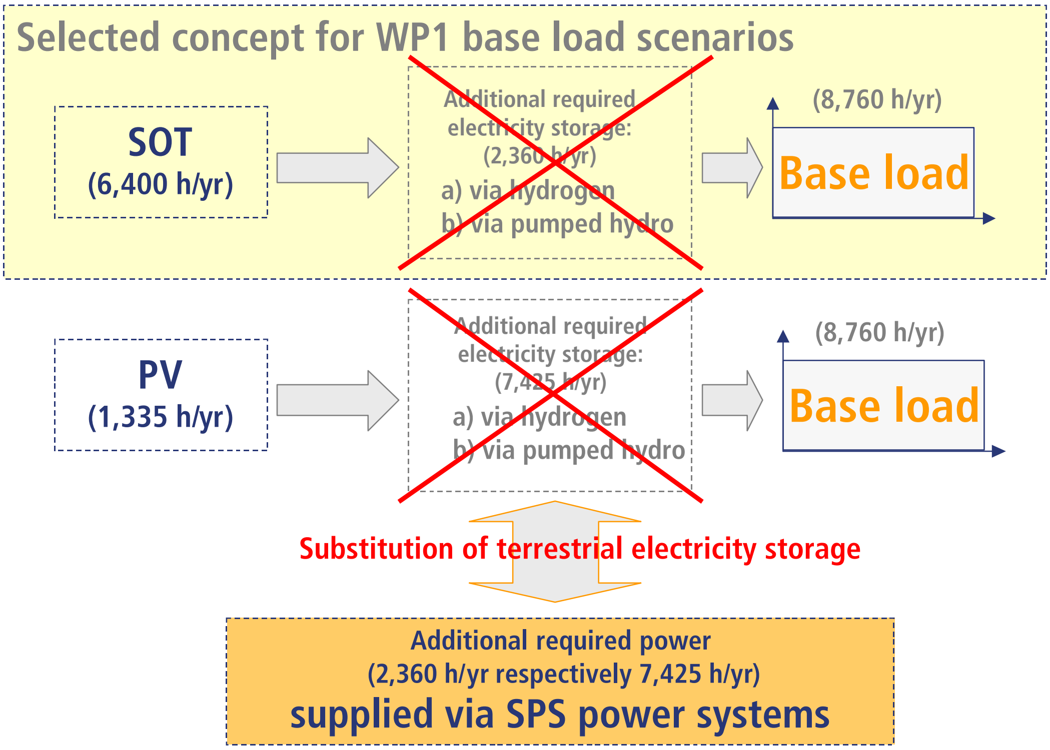

Figure 8-5: Synergies between SPS and SOT respectively PV for terrestrial electricity storage substitution: SPS systems deliver the amount of electricity additional required for terrestrial WP1 base load scenarios

Based on the learning curves for SOT / PV and SPS systems (described in the previous chapters) the levelized energy costs (LEC) for electricity supply drops with rising capacities of the total installed power systems. Table 8-1 and Table 8-3 show the technical data and resulting LEC for SOT respectively PV and SPS for combined scenarios without electricity storage for terrestrial systems. The SPS systems are based on the WP1 and WP2 scenario concepts. For LEC evaluations of the SPS systems three launch cost parameter assumptions are selected by means of average launch cost targets of 1,000 EUR/$kg_{payload}$, 600 EUR/$kg_{payload}$ and 200 EUR/$kg_{payload}$.

Scenario	SOT (without storage)			SPS (operated only for terrestrial storage substitution)					
	(without electricity storage via hydrogen or pumped hydro)			Installed capacity [GW_e]	Power supply [2] [TWh/yr]	LEC **without launch** [EUR/kWh]	LEC [EUR/kWh_e] **including launch** with launch cost target parameter:		
	Installed capacity [GW_e]	Power supply [1] [TWh/yr]	**LEC [3] [EUR/kWh]**				**1,000 EUR/kg**	**600 EUR/kg**	**200 EUR/kg**
0.5 GW	0.5	3.2	**0.041**	0.5	1.2	0.934	**1.733**	**1.413**	**1.094**
5 GW	5	32	**0.036**	5	12	0.137	**0.309**	**0.240**	**0.171**
10 GW	10	64	**0.035**	10	24	0.143	**0.325**	**0.253**	**0.180**
50 GW	50	320	**0.032**	50	118	0.106	**0.288**	**0.215**	**0.142**
100 GW	100	640	**0.031**	100	236	0.102	**0.284**	**0.211**	**0.138**
500 GW	500	3,200	**0.029**	500	1,180	0.102	**0.290**	**0.215**	**0.140**

[1] SOT full load hours: 6,400 h/yr.

[2] SPS power supply = required electricity storage in terrestrial scenarios with SOT plants = 2,360 equivalent full load hours/year.

[3] Reduction of LEC due to effect of learning curve for SOT plants (see 2.2.3)

Table 8-1: Synergies for WP1 scenarios: SPS systems supply additional required power for base load scenarios to substitute amount of terrestrial electricity storage calculated for WP1 SOT scenarios

As shown in Table 8-1 the electricity supplied by SOT is in all scenario cases the least cost option. Table 8-2 indicates that SPS systems which are only operated for terrestrial storage substitution are not cost competitive with 'WP1 scenarios' based on SOT systems comprising an additional electricity storage (both hydrogen and pumped hydro storage).

Scenarios [GW]	SOT (with storage): with hydrogen storage LEC [EUR/kWh$_e$]	SOT (with storage): with pumped hydro storage LEC [EUR/kWh$_e$]	SPS (operated only for terrestrial storage substitution): LEC **without launch** [EUR/kWh$_e$]	SPS: LEC [EUR/kWh$_e$] **including launch** with launch cost target parameter: 1 000 EUR/kg$_{payload}$	600 EUR/kg$_{payload}$	200 EUR/kg$_{payload}$
0.5	**0.090**	**0.058**	0.934	**1.733**	**1.413**	**1.094**
5	**0.082**	**0.053**	0.137	**0.309**	**0.240**	**0.171**
10	**0.080**	**0.051**	0.143	**0.325**	**0.253**	**0.180**
50	**0.076**	**0.049**	0.106	**0.288**	**0.215**	**0.142**
100	**0.075**	**0.047**	0.102	**0.284**	**0.211**	**0.138**
500	**0.076**	**0.050**	0.102	**0.290**	**0.215**	**0.140**

Table 8-2: Comparison of LEC of SPS systems with LEC of SOT systems with electricity storage via hydrogen respectively pumped hydro calculated for WP1 base load scenarios

Figure 8-6 summarizes the cost results for SOT and SPS systems operated for part load (~2,360 h/yr equivalent full load period) and full load (8,760 h/yr equivalent full load period) respectively. SPS systems which are only operated for the substitution of additionally required terrestrial storage of SOT plants achieve ~2,360 full load hours per year. This leads to higher levelized energy costs even without launch costs compared with SOT plants with hydrogen or pumped hydro storage. For 500 GW base load scenarios SPS systems have to supply power for terrestrial storage substitution with resulting costs between 0.047 and 0.021 EUR/kWh$_e$ for scenarios with hydrogen and pumped hydro storage respectively. As can be seen in Figure 8-6 SPS systems achieve only targeted cost range for scenarios which are based on hydrogen storage option with launch cost targets below 200 EUR/kg$_{payload}$. The substitution of pumped hydro storage of terrestrial SOT plants by SPS systems – even operated at base load – would not lead to cost benefits and scenario synergies. The combination of SPS systems with SOT systems for the substitution of terrestrial hydrogen storage would only lead to positive cost effects if SPS systems are operated at base load and launch cost targets are below 200 EUR/kg$_{payload}$. But if SPS systems are operated at base load mode in combination with terrestrial SOT systems, a total electricity surplus of around 6,400 h/yr or ~73% is produced. As a results, the combination of SPS systems and SOT systems for base load scenarios leads to no positive synergy effects due to higher cost if SPS systems are operated only for terrestrial storage substitution or due to the overproduction of electricity if SPS systems are operated at base load mode to achieve lower energy cost with target launch cost far below 200 EUR/$kg_{payload}$.

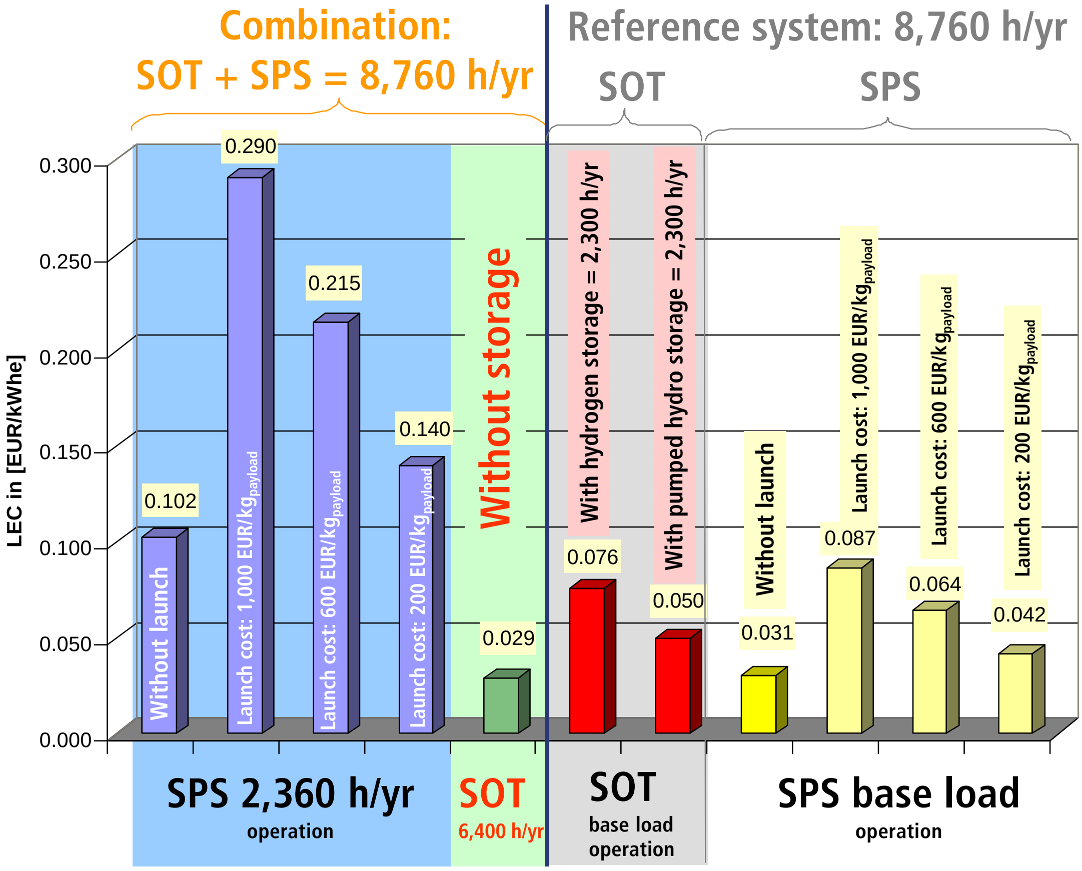

Figure 8-6: Levelized energy costs for different SOT and SPS systems for 500 GW base load scenario.

The following Table 8-3 shows the results for investigated synergy scenarios between terrestrial PV systems combined with SPS systems. In the previous 'WP1 base load' discussion, PV technology was not selected due to high costs for electricity supply and low equivalent full load hours for base load operation, see also discussion in 'WP1 chapter'.

Scenario	PV			SPS					
	(without electricity storage via hydrogen or pumped hydro)			Installed capacity [GW_e]	Power supply [2] [TWh/yr]	LEC **without launch** [EUR/kWh]	LEC [EUR/kWh_e] **including launch** with launch cost target parameter:		
	Installed capacity [GW_e]	Power supply [1] [TWh/yr]	**LEC [EUR/kWh]**				**1,000 EUR/kg**	**600 EUR/kg**	**200 EUR/kg**
0.5 GW	0.5	0.4	**0.517**	0.5	4.03	0.297	**0.551**	**0.449**	**0.348**
5 GW	5	3.5	**0.401**	5	40.3	0.044	**0.098**	**0.076**	**0.054**
10 GW	10	7.1	**0.357**	10	80.5	0.046	**0.103**	**0.080**	**0.057**
50 GW	50	35	**0.269**	50	403	0.034	**0.092**	**0.068**	**0.045**
100 GW	100	71	**0.240**	100	805	0.032	**0.090**	**0.067**	**0.044**
500 GW	500	353	**0.190**	500	4,027	0.033	**0.092**	**0.068**	**0.045**

[1]. **PV full load hours: 1,335 h/yr.**

[2] SPS power supply = required electricity storage in terrestrial scenarios with SOT plants = 7,425 equivalent full load hours/year.

Table 8-3: Synergies for WP1 scenarios: SPS systems supply additional required power for base load scenarios to substitute amount of terrestrial electricity storage calculated for WP1 PV scenarios

Table 8-3 indicates that in the synergy scenarios based on 'WP1 base load' assumptions with PV technology for terrestrial power supply, SPS systems would have the potential to produce electricity significantly below the cost of terrestrial power plants. This result would open the discussion from the economic point of view if such a combination would be realistic or if concepts with only SPS systems would make more economic sense. Both systems, PV and SPS, would then be in direct competition to each other. See further discussion on this topic in subchapter 8.3.

b) Non-base load

For chapter 6 'WP2 non-base load' only PV systems were selected for the terrestrial scenarios for the power levels of 0.5 GW / 5 GW / 10 GW / 50 GW / 100 GW and 150 GW. SOT systems are not selected and evaluated due to the low equivalent full load hours of non-base load scenarios. As described in chapter 2.2 SOT systems achieve 6,400 equivalent full load hours per year and thus oversized for WP2 scenarios which require equivalent full load periods between ~5 to ~1,700 hours per year. Like solar thermal power plants, solar power satellites require high utilization of power generation as seen in the results of WP1 and WP2. Table 8-4 shows the relation between the load factor (in equivalent full load hours per year) of a SPS system and the levelized energy costs (LEC). The higher the load factor or utilization grad of the system, the lower the resulting LEC for the SPS systems.

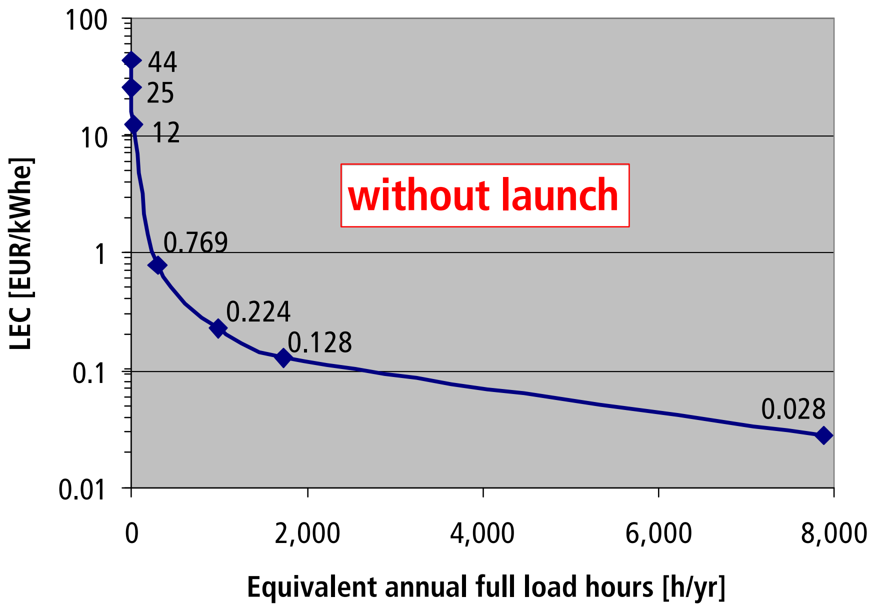

Table 8-4: SPS power generation costs depending on the load factor (equivalent annual full load hours). SPS data are based on the 150 GW scenario system for non-base load operation.

Scenarios for the combination of PV and SPS for non-base load power supply based on assumptions of WP2 would cause lowest load factors for SPS. Therefore a combined scenarios for substitution of terrestrial storage based on WP2 scenario is not further investigated and evaluated.

For supply of non-base load power through SPS systems high load factors are required to supply electricity at a cost competitive basis. Such an advanced scenario is presented and discussed in chapter 8.3.3.

8.1.3 Conclusion from terrestrial perspective

Some synergies discussed from a terrestrial perspective may foster the deployment of terrestrial solar power systems, such as a potentially common technology and resource basis for PV production or the substitution of terrestrial storage requirements implied by the base load and non-base load scenario design respectively. However, these synergies do not seem to be on a mutual basis. In case of a common resource / production basis, the terrestrial target market for space-based solar power may even be disturbed by offsetting terrestrial installations.

Under the scenario assumptions defined, a combined scenario with solar thermal power plants (SOT) and solar power satellites (SPS) would not result in mutual benefits if compared to WP1 base load scenarios based only on SOT or SPS respectively.

The substitution of terrestrial storage by SPS would not result in cost reduction if SPS is only operated at low utilization i.e. for the sole purpose of terrestrial storage substitution. If SPS systems would be operated at higher utilization (maximum of 8,760 equivalent full load hours per year) levelized energy costs of SPS systems would be significantly lower. Average target launch costs below 200 $EUR/kg_{payload}$ are required in order to beneficially substitute storage requirements which result from SOT base load scenarios based on hydrogen storage. Even lower average launch cost targets are required for the beneficial substitution of terrestrial pumped hydro storage which are required in conventional SOT base load scenarios.

If terrestrial and space based systems were both operated on base load operation modes, an electricity surplus of at least 6,400 equivalent full load hours per year or 73 % of the total annual power would be generated. Thus, to avoid a direct competition of both systems in a combined base load scenario, SPS systems should be operated on part load operation mode to complement terrestrial SOT systems without storage. However, this option would not result in cost reductions, yet would cause higher energy costs than calculated for WP1 'base load' scenarios based on terrestrial solar power plants solely.

Non-base load scenarios would require even lower equivalent full load hours for both systems. Thus a combination of non-base load SPS systems which are operated at low utilization with terrestrial non-base load systems would result in higher electricity costs. Thus, no synergies could be identified for a combined scenarios for terrestrial non-base load storage substitution by SPS. In brief, although SOT systems require large amounts of storage, it is used only low load factor due to SOT's large self storage capacity. Consequently substitution of this storage by space based systems would require rectennae to operate at low load factors. This can be economic only if the satellites supplying then too deliver power to rectennae outside Europe as discussed in section 8.3.

8.2 Space and terrestrial synergies from the space perspective

The non-base load scenario analyzed in Section 6 considers a supply of 150 GW operated at an average load-factor of 20% (ranging from more than 37% to less than 0.1%), as illustrated in Table 6-1. However, 150 GW is less than half the non-base load demand forecast for Europe in 2030 in Figure 4-5 and Figure 4-6, which show a continuous supply of 255 GW out of a maximum of 570 GW. This is important because space-based solar power systems would have considerable capacity to supply non-base load power economically at load-factors between their maximum of 97% (or 100% with a small amount of storage, as discussed in Section 5.2.1 'Selected concepts' and about 30%. Except in special cases, and/or in a very large capacity system, space-based solar power systems would be unlikely to be able to economically supply non-base load power at load-factors less than 30%, as concluded in Section 6. However, the ability to supply the 165 GW needed in Europe in 2030 at load-factors between 100% and 37% provides the basis for important synergies between terrestrial and space-based solar power systems, which are analyzed in this Section.

In order to understand these synergies, it is necessary to analyze the potential for flexible operation of solar power satellites and rectennae, which was done in Section 3.3 'Flexible operation of solar power satellites and rectennae'. In this Section potential synergies between terrestrial and space-based solar power are evaluated from space perspective, including for both base load and non-base load supply. In Section 8.2.5 'Other potential synergies with SPS', synergies are considered between the development of solar power satellites and rectennae and a range of other systems, all of which need to be considered in order to understand the potential costs and benefits of developing space-based solar power supply for Europe.

8.2.1 Space and terrestrial solar cell technology

World-wide annual production of solar cells for terrestrial use in 2002 was 500 MW, of which Japanese companies produced more than 50%. Production is predicted to reach 1 GW in 2004, which is already 10 times the volume of production at the time of the Fresh Look study [NASA 1997] (see also photovoltaic (PV) technology discussion in chapter 2.1). The continuing growth of such mass-production capabilities is likely to have beneficial effects for space-based solar panel production.

8.2.2 Combined terrestrial solar power plants and rectennae

Terrestrial solar power systems which use large contiguous areas of land would create the potential to use the same land for collecting both direct solar power and microwave power transmitted from satellites. Some designs of rectenna use an antenna surface that is largely transparent to sunlight, allowing 80 - 90% of sunlight to pass through; these include distributed diode arrays and wire reflector designs. It would therefore be possible to place such a rectenna surface over a terrestrial photovoltaic (PV) power plant (possible undesired effects – such as an overproportional decrease of PV power output due to partial shadowing of the PV cell/module caused by rectenna constructions – and influencing parameters are discussed in chapter 2.1.2 ('System design'). Moreover, targeted research could probably produce a panel design which integrates photovoltaic and microwave absorption capabilities in the same surface, which could probably reduce both costs and losses of power even further (possible impacts on the PV power plant from electromagnetic interference would then have to be examined which could not be done in the framework of this study). The co-siting is less promising for solar thermal power plants, which are more dependent on direct sunlight, and of which designs using a central tower would not offer economies in combining mechanical structures.

Combining a rectenna with a terrestrial solar power system may reduce the capital cost per kW of output capacity of the rectenna system. From the point of view of rectenna operations, reducing the relevant cost of land, support structure and some of the electrical systems would enable the rectenna to be operated economically at lower load-factor than a stand-alone rectenna, and therefore with greater flexibility.

It should be noted, however, that co-siting a rectenna is appropriate only for the case of large terrestrial solar power plants covering large contiguous areas, typically several kilometers across. (In 2003 Mitsubishi Electric Corporation proposed a system for recharging mobile telephone batteries using a satellite to transmit microwave power over large cities such as Tokyo (www.ipc.shizuoka.ac.jp/~tykuwab/energyin.htm); the large proportion of the transmitted power that would be wasted is estimated to be harmless. However, it seems unlikely that such a wasteful system of delivery to many small receivers would be implemented for large-scale power generation, even if the losses were judged to be harmless, and even if most buildings' roofs came to be covered with photovoltaic panels incorporating rectenna elements. In order to be within internationally accepted safety standards, the maximum intensity could be only 10 W/m², or 10 MW/km² (i.e. about 10% of the output/m² of a rectenna), of which only perhaps 30% might be utilized, at the cost of considerable "microwave pollution".)

In order to estimate the cost of a rectenna combined with a terrestrial solar power plant, the break-down of rectenna cost components in Table 3-3 is used. Based on this cost breakdown, Table 8-5 shows an estimate of the incremental cost of a rectenna co-sited with a terrestrial solar power plant, based on the following assumptions: the incremental cost of Land and Primary Structure are zero; and the rectenna's DC Distribution and Utility Interface costs are each reduced by 1/3 (due to scale factors and sharing of fixed costs). NB the Land Cost in the Fresh Look study is \$1.3 /m²; to the extent that this underestimates the cost of land for rectennae in Europe, the advantage of co-siting a rectenna with a terrestrial solar power plant would increase.

	million US$$_{1979}$	million EUR$_{2000}$	
Land cost per m²	0	0	(85 km² @ 0 $/m²)
Primary structure	0	0	
RF-DC conversion	661	1058	(Ditto above)
DC distribution	179	286	
Control system	61	98	
Utility interface	449	719	
Total	1350	2160	

Table 8-5: Incremental cost of rectenna co-sited with terrestrial solar power plant

On this approximation, the incremental cost of a rectenna sited over a terrestrial solar power station would be approximately 65% that of a stand-alone rectenna. Although the cost figures for the rectenna tabulated in [Harron 1981] are approximately 10% lower than the figures quoted for the 1979 Reference System study in Table 6-4 of the Fresh Look study [NASA 1997], a 35% cost reduction is probably a reasonable estimate. Table 6-1 (from [Harron 1981]) shows that the ground systems represented some 19% of the total SPS Reference System cost[7]. In this case, combining a rectenna with a terrestrial solar power plant would reduce the overall cost of space-based power by (0.35 x 0.19), that is some 6.7%. However, reducing the rectenna component of the cost by 35% would make the use of the rectenna significantly more flexible, being economical at even lower load-factors. (The loss of solar energy due to shading depends on the architecture of both the PV and rectenna system. The problem of power mismatch due to partial shading is discussed in Section 2.1.2 and would need to be included in an analysis of the revenues.)

a) European conditions

The cost of a rectenna under European conditions is estimated at 13.3% of the total system cost in Section 3.3.1 above. Reducing this cost by 35% would therefore reduce the system cost by some 4.7%, and the economic operating range of the rectenna would be extended as shown in Figure 8-7. Thus, for example, when receiving power from a satellite operating at 92% load factor, the rectenna could be economically operated at a load factor less than 50%. This is a considerable improvement over the same case of a single rectenna shown in Figure 3-13. Similar analyses could be performed for the case of

[7] The NASA Fresh Look Study does not provide a breakdown of rectenna sub-system costs; consequently in order to estimate the cost of a co-sited rectenna, data from the 1979 Reference System study and related reports has to be used.

a co-sited rectenna as in the other cases described above in Section 3.3 in Figure 3-14 and Figure 3-15.

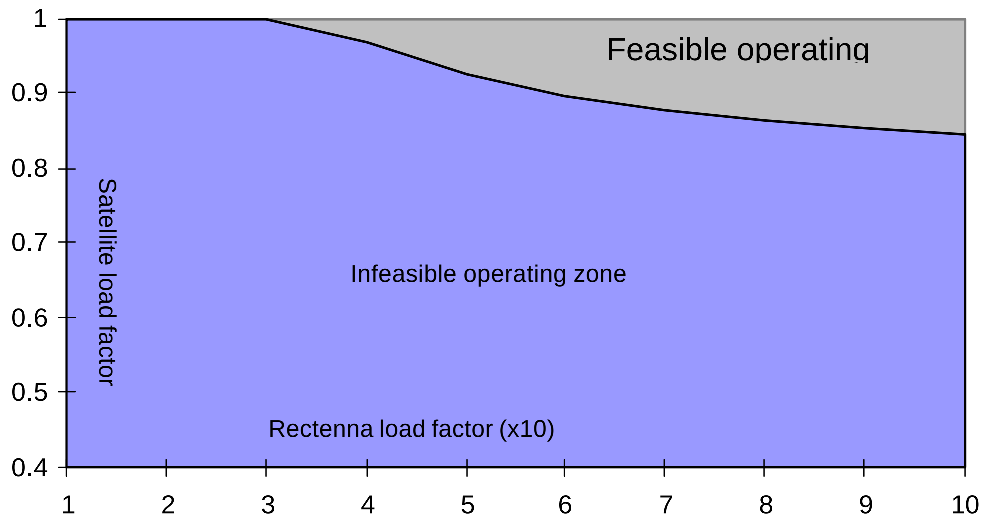

Figure 8-7: Feasible operations for rectenna co-sited with terrestrial solar power plant

Section 5.1.2 assumes that if terrestrial solar thermal power plants were used to supply 500 GW for Europe, either 106.8 GW or 220 GW would be generated in north Africa (depending on the storage technology used). Co-siting rectennae with such plants could potentially reduce the land area used, and may reduce the cost of the rectennae. If operated as a winter power supply for Europe it could also provide a summer electricity supply for countries hosting the facilities (as discussed in Section 8.3).

b) Oversized terrestrial sites

A special case of interest for integrating terrestrial and space-based power systems is the possible use of terrestrial solar power systems spread over very large areas of desert (and/or sea surface), which would be much larger than the minimum area needed for a rectenna [Kuwano 1991]. The use of such an area for simultaneous reception of microwave power from space would be facilitated since it could accommodate the "exclusion-zones" that are planned around commercial rectennae, thereby reducing the effective cost per unit of rectenna area.

If developed, such large-scale "Energy farms" in north Africa could lead to re-optimization of the microwave power transmission system. This is because the size of the transmitting and receiving antennae of a space-based solar power system are inversely related. Hence reducing the cost per unit area of the rectenna would increase its optimum area and reduce the optimum area of the space-based antenna, thereby reducing the mass and cost of the satellite. It could also reduce the pointing accuracy required for the microwave power-beam, thereby relaxing the technical requirements for the satellite, and reducing its costs further, as discussed further in Section 3.4.3.

8.2.3 Combined terrestrial and space-based solar power: base load scenarios for North African installations

The largest of all scenarios considered in this study (500 GW base load) requires terrestrial installations in North Africa. As a case-study for combining terrestrial and space-based systems used for supplying base load power, two cases are considered: Table 8-6 shows the effect of dessert land area reduction if the terrestrial share of SOT installations sited in North Africa are substituted by rectennae; Table 8-7 shows the effect of dessert land area reduction if solar thermal power (SOT) plants sited in North Africa are co-sited with rectennae.

	Space-based	SOT with hydrogen storage	Space-based	SOT with pumped hydro storage
Baseload output GW	220	220.2	107	106.8
Number of units	44	2414	21.4	826
Unit nominal power level GW	5	0.11	5	0.15
(Rectenna surface area sqkm)	50.44		50.44	
Rectenna land area sqkm	79.20		79.20	
Total land area sqkm	3485	54315	1695	11481
Storage area sqkm		*)		759 **)
Reduction in land area sqkm	50830		10542	
	93.6%		91.8%	

*) land area of hydrogen storage included in total land area

**) required land area for pumped hydro storage lakes

Table 8-6: North Africa land use for base load supply scenario with solar thermal (SOT) power plants or SPS rectennae respectively.

	Space-based	SOT with hydrogen storage	Space-based	SOT with pumped hydro storage
Baseload output GW ***)	207	13.3	93	13.7
Number of units	41.4		18.6	
Unit nominal power level GW	5		5	
(Rectenna surface area km²)	50.44		50.44	
Rectenna land area km²	79.20		79.20	
Total land area km²	3279		1473	
Storage area km²		*)		97 **)
Reduction in land area km²	51036		10670	
Reduction in land area and storage %	94.0%		92.9%	

*) land area of hydrogen storage included in total land area

**) required land area for pumped hydro storage lakes

***) output estimation: SOT plants are installed on rectennae areas;
rectennae output are limited by amount of resulting SOT output

Table 8-7: North Africa land use for base load supply scenario (combined rectenna + solar thermal power plant)

Table 8-6 and Table 8-7 show that if space-based solar power supply was cost-competitive it could enable large savings in dessert land area for the 500 GW scenario – namely 52,000 km², or 96%, for the hydrogen storage case, and 10,000 km², or 92%, for the pumped hydro case. These large savings arise from the significant difference in average base load output per unit of land area for the three systems: 63 W/m² for rectennae, 8 W/m² for solar thermal using hydrogen storage, and 9 - 11 W/m² for solar thermal using pumped hydro storage. Terrestrial photovoltaic systems are lower than solar thermal due to the energy mismatch, requiring larger storage capacity. Such large land area savings would have a range of benefits. In Section 4.5 'Land use' it is explained that the cost of land is not estimated in the present study; it is therefore useful to describe some of the benefits qualitatively. However, the co-siting of rectennae with SOT installations would require a further technical verification as discussed in Section 8.2.2.

Collecting centrally solar energy for power production greatly reduces the value of land that might be used for agriculture. Although the land to be used for this purpose will be selected as land with the lowest value in alternative uses, growth of population through the 21st century may create increasing demand for land, making the accommodation of ever-growing areas for power production more difficult and expensive. Since sites suitable for pumped-hydro power storage are limited geographically, means of reducing the scale of storage needed in order to accommodate terrestrial solar power are valuable.

8.2.4 Combined space-based solar power systems with terrestrial storage for non-base load SPS scenarios

In addition to the assumptions made for non-base load scenario calculation in Section 6, various system design/operation options are discussed in the course of this Section. Thereby, focus is not put on synergies with terrestrial solar power generation systems but on the investigation of an optimized system e.g. via flexible operation of satellites or comprising terrestrial storage options.

As discussed in Section 3.3, space-based solar power systems would have the capability to supply non-base load power at relatively high load-factors, i.e. from less than 97% down to perhaps 30%. Using space-based systems, non-base load power could be supplied in two ways, namely by using rectennae supplying continuous power and charging storage systems which supplement the rectenna output during the appropriate periods, or by operating rectennae at low load factors. These two approaches are considered in turn as four different cases: a) hydrogen energy storage, b) pumped hydro storage, c) fixed '1:1' satellite:rectenna pairs (as assumed for chapter 6), and d) non-base load rectennae supplied by base load satellites (as assumed for chapter 5).

For each case a system of 100 GW output is considered for a parametric analysis of a range of load-factors[8].

Table 8-8 shows the space-based solar power generating capacity, the electrolyzer capacity, the hydrogen energy storage capacity, and the fuel-cell generation capacity needed to supply 100 GW at different load factors. The system size and cost are strongly influenced by the storage capacity, which is determined by the number of storage cycles. Following the assumption in Table 4-6, 50 loading/unloading cycles per year are assumed.

[8] In order to illustrate the matter in a simple way, the different means of supplying 100 GW capacity are compared.

Load factor %	Space-based Capacity GW	Electrolyser Capacity GW	Storage Capacity* TWh	Fuel cell Capacity GW
100%	100	0	0	0
90%	96.2	96.2	0.60	3.8
80%	91.8	91.8	1.15	8.2
70%	86.7	86.7	1.63	13.3
60%	80.8	80.8	2.02	19.2
50%	73.7	73.7	2.31	26.3
40%	65.1	65.1	2.45	34.9
30%	54.5	54.5	2.39	45.5
20%	41.2	41.2	2.06	58.8
10%	23.7	23.7	1.34	76.3

*: Assumes 50 load/unload cycles/year

Table 8-8: Hydrogen storage system for non-base load supply

Table 8-9 shows the space-based solar power generating capacity, the pumping/ generation capacity, and the pumped hydro energy storage capacity needed to supply 100 GW at different load factors. NB the pumping/generation capacity is dominated by the storage function at higher load factors, and by the generation function at lower load factors.

Load factor %	Space-based Capacity GW	Pumping / Generating Capacity GW	Storage Capacity* TWh
100%	100.0	0	0
90%	91.4	91.4	1.36
80%	82.5	82.5	2.46
70%	73.3	73.3	3.27
60%	63.8	63.8	3.80
50%	54.1	54.1	4.02
40%	44.0	56.0	3.93
30%	33.5	66.5	3.49
20%	22.7	77.3	2.71
10%	11.6	88.4	1.55

*: Assumes 50 load/unload cycles/year

Table 8-9: Pumped hydro storage system for non-base load supply

Table 8-10 shows the satellite and rectenna capacity used in cases c) and d). For a fixed satellite:rectenna pair (case c)) used at low load factors the full capital cost is allocated to every case. For a satellite operating at maximum load factor (case d)) only the relevant proportion of its capital cost needs to be allocated, but the whole rectenna cost is allocated. An actual system would lie somewhere between these two cases.

Load factor %	Fixed SPS capacity GW	Flexible space system	
		Satellite cap'y GW	Rectenna cap'y GW
100%	100.0	100.0	100.0
90%	100.0	90.0	100.0
80%	100.0	80.0	100.0
70%	100.0	70.0	100.0
60%	100.0	60.0	100.0
50%	100.0	50.0	100.0
40%	100.0	40.0	100.0
30%	100.0	30.0	100.0
20%	100.0	20.0	100.0
10%	100.0	10.0	100.0

Table 8-10: Satellite and rectenna capacities for non-base load supply

The capital costs of the different components of the systems defined in the previous tables are shown in Table 8-11 through Table 8-13. Values for the storage systems are taken from Table 4-3 and Table 4-4. The capital costs of the space-based system and rectenna are taken from Section 3.3.1 and multiplied by 1.06 (conversion factor to adapt to current values) to give 4,942 EUR/kW, of which 13.3% or 657 EUR/kW is the rectenna cost. (All SPS costs include launch costs assumption of 121 EUR/$kg_{payload}$ assumed by [NASA 1997]).

Cost of SPS EUR/kW	4942
Cost of Electyrolyser EUR/kW	500
Cost of Storage EUR/kWh	117
Cost of H2 fuel cells EUR/kW	500

Load factor %	K Cost of SPS Capacity Billion EUR	K Cost of Electrolyser Billion EUR	K Cost of Storage cap'y* Billion EUR	K Cost of Fuel cells Billion EUR	Total K Cost Billion EUR
100%	494.2	0.0	0	0	494.2
90%	475.3	48.1	70	1.9	595.8
80%	453.7	45.9	135	4.1	638.2
70%	428.5	43.4	191	6.6	669.2
60%	399.1	40.4	237	9.6	685.8
50%	364.1	36.8	270	13.2	684.0
40%	321.7	32.5	286	17.5	657.9
30%	269.4	27.3	280	22.7	599.1
20%	203.4	20.6	241	29.4	494.6
10%	117.2	11.9	156	38.1	323.6

*: 39 EUR/Nm3 & 2 Nm3/hr = 1kW taken from Section 4.4.2

Table 8-11: Capital cost of hydrogen storage system at different load-factors. All SPS costs include launch costs assumption of 121 EUR/kg$_{payload}$ assumed by [NASA 1997]

Cost of SPS EUR/kW	4942
Cost of Pump EUR/kW	600
Cost of storage EUR/kWh	12

Load factor %	K Cost of SPS Capacity Billion EUR	K Cost of Pumping/Gen. Billion EUR	K Cost of Storage Billion EUR	Total K Cost Billion EUR
100%	494.2	0	0	494.2
90%	451.6	54.8	16.3	522.7
80%	407.6	49.5	29.5	486.5
70%	362.2	44.0	39.3	445.5
60%	315.4	38.3	45.6	399.4
50%	267.1	32.4	48.3	347.9
40%	217.2	33.6	47.1	298.0
30%	165.7	39.9	41.9	247.5
20%	112.3	46.4	32.5	191.2
10%	57.1	53.1	18.6	128.8

Table 8-12: Capital cost of pumped hydro storage system at different load-factors. All SPS costs include launch costs assumption of 121 EUR/kg$_{payload}$ assumed by [NASA 1997]

Load factor %	K Cost of fixed 1:1 SPS Billion EUR	Flexible space-based system		
		Satellite Billion EUR	Rectenna Billion EUR	Total K Cost Billion EUR
100%	494.2	428.5	65.7	494.2
90%	494.2	385.6	65.7	451.4
80%	494.2	342.8	65.7	408.5
70%	494.2	299.9	65.7	365.7
60%	494.2	257.1	65.7	322.8
50%	494.2	214.2	65.7	280.0
40%	494.2	171.4	65.7	237.1
30%	494.2	128.5	65.7	194.3
20%	494.2	85.7	65.7	151.4
10%	494.2	42.8	65.7	108.6

Table 8-13: Capital cost of space-based systems at different load-factors. All SPS costs include launch costs assumption of 121 EUR/kg$_{payload}$ assumed by [NASA 1997]

Figure 8-8 shows the capital costs of these four options for a range of load factors. The cost of a space-based system (including launch costs of 121 EUR/$kg_{payload}$) would lie somewhere between the cost of a 1:1 SPS:rectenna system and a non-base load rectenna receiving power from a base load satellite. Its costs are therefore comparable with using pumped hydro to convert base load space-based power into non-base load power, but less than using hydrogen for electricity generation.

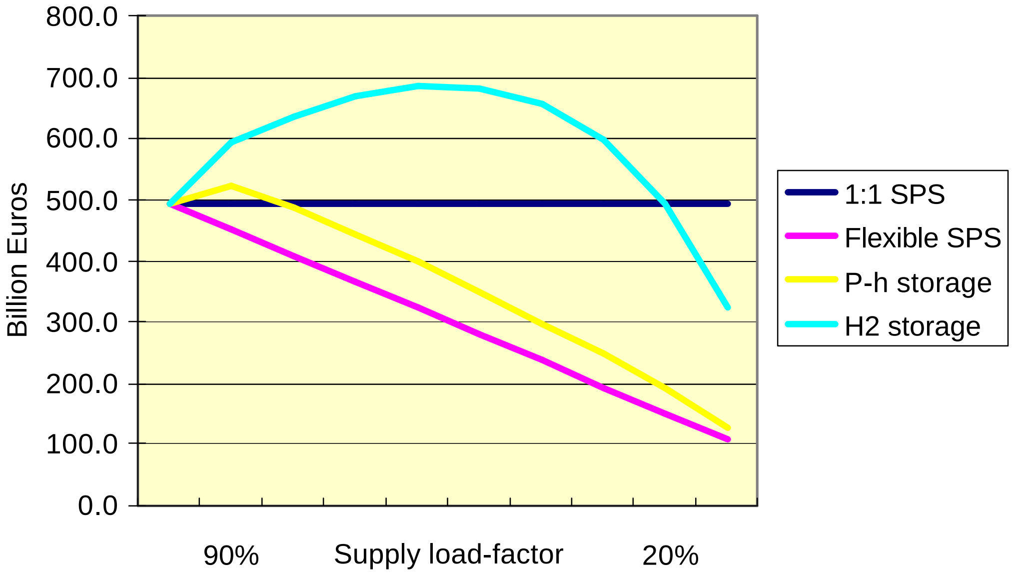

Figure 8-8: Capital costs of non-base load power options (1). SPS costs include launch costs assumption of 121 EUR/$kg_{payload}$ assumed by [NASA 1997]

The decline that is seen in system capital cost as the load factor declines reflects the falling proportion of the satellite cost that is allocated, since a growing share of the satellite cost is allocated to other users. If it is assumed that only a fraction of the theoretically possible network synergies are achieved, a proportionately larger share of the satellite capital costs must be allocated.

In Figure 8-9 the two additional cases of SPS2 and SPS3 show the effect of achieving less than the maximum theoretical savings from "network synergies". In SPS2 80% of the synergies are achieved; in SPS3 60% of the synergies are achieved. (The 1:1 SPS:rectenna case is where no synergies are achieved.) As would be expected, achieving less synergies raises the capital cost of the SPS system needed to supply 100GW at a given load factor. As a result, pumped storage becomes competitive at load factors of about 35% and 55% respectively. While the figures are only approximate, this fits the pattern that space-based systems would generally be competitive at higher load-factors.

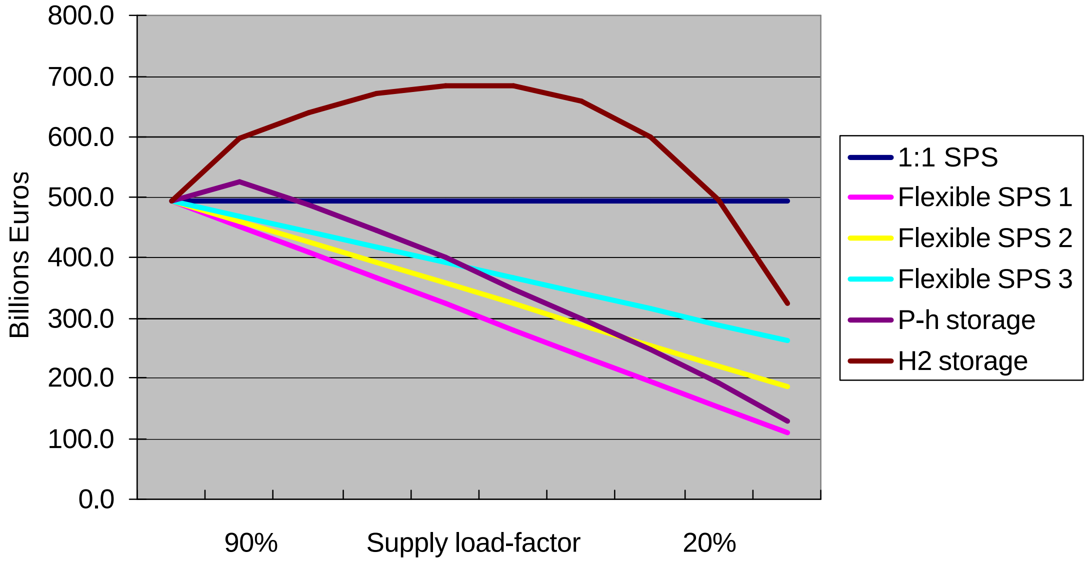

Figure 8-9: Capital costs of non-base load power (2). SPS costs include launch costs assumption of 121 EUR/kg$_{payload}$ assumed by [NASA 1997].

a) Complementarity of terrestrial and space-based solar power systems

Like all estimates relating to space-based solar power, the above calculations depend on whether the economic cost targets described in the Fresh Look study, and particularly the launch cost targets discussed in this report, could be met in practice. However, if solar power satellites were to become competitive (through the development of sufficiently low-cost launch vehicles and other technological capabilities), its potentially high availability compared to terrestrial solar power would greatly reduce land area needs.

In summary, the operation of terrestrial and space-based solar power supply systems can be seen to be complementary. That is, terrestrial solar power systems would be designed initially with storage capacity sized to raise their reliability in supplying some portion of daytime power to a level acceptable to electric utilities. As costs fell, these systems could supply reliable power at progressively higher load-factors, using progressively larger storage capacity, and eventually contributing to base load power. Space-based systems would be designed for the opposite purpose; primarily supplying base load power and non-base load power at relatively high load-factors. If space-based systems' costs fell sufficiently they could supply power at progressively lower load-factors, through operating rectennae flexibly as network-economies improved, as discussed in Section 8.3.3b).

8.2.5 Other potential synergies with SPS

The development of space-based solar power supply systems would lead to development and use of a range of new technological capabilities which may have synergies with many other systems. That is, if space-based power systems were estimated to be competitive in some markets and so were constructed and put into operation, a range of new business opportunities may arise which could significantly increase the project’s economic value.

a) Technological synergies

The technological capabilities that would need to be developed in order to deliver power from space include large space structures, large-scale solar power generation, large-scale wireless power transmission and reception, and low-cost launch systems for both cargo and people. These and others could be used for a progressively growing range of additional uses.

- Combination with agriculture

Construction of a rectenna over tens of km² of land would not prevent the use of the land for some purposes, including particularly for agriculture. In recent years large investments have been made in the use of greenhouses to maximize agricultural productivity, particularly in countries with high insolation, such as southern Spain. Such structures could readily be combined with a rectenna, in effect acting as its mechanical support structure, and so rectenna construction could be combined with agricultural production.

Another application that has been considered in this context is the siting of rectennae over aquaculture facilities such as prawn-farms, which the Chairman of the Japanese SPS Research Society, Professor Hideo Matsuoka has started to investigate with colleagues in Malaysia [Matsuoka 2000]. Although aquaculture is not yet a major activity in Europe, it is a rapidly growing industry with major growth prospects world-wide. Its potential for synergy with rectenna siting is therefore likely to grow in future.

- Lunar resource utilization

There is a substantial literature on the use of lunar resources for manufacturing solar power satellites. This development would be stimulated by the creation of demand for hundreds of thousands of tons of materials in geo-stationary orbit, and could greatly reduce the use of terrestrial energy and materials, thereby achieving a faster energy payback time for space-based solar power. In early 2004 the US president announced a plan to devote a major part of NASA’s budget in coming decades to development and operation of a lunar surface base and to develop space resources. The realization of this plan could greatly facilitate this development.

There is also a literature on delivering power via solar-generated microwave beams transmitted from the lunar surface to Earth. This would involve much of the same technology as orbiting satellite systems, while benefiting from the stable physical base for solar collectors and transmitting antennae that could cover an area many times larger than in orbiting systems. The disadvantages would be the approximately 10 times longer power transmission distance, the non-geosynchronous orbit necessitating the use of long-distance terrestrial power transmission and/or orbiting power reflector systems, and the 28-day lunar day-night cycle (necessitating, at worst, twice the area of solar panels). Developing the technological capability to deliver power to Earth from orbiting satellites would have many synergies with a lunar system, and would reduce the investment needed to realize it.

- Power relay satellite

Large, orbiting microwave-power reflector-antennae have been proposed for transmitting power between terrestrial sites, such as from a desert-based solar power plant to a rectenna near a major demand center. Another means of utilizing this capability would be to site a receiver/transmitter system beside a large energy storage system, thereby linking it to other facilities in an extended grid to which it was not connected by cables. Orbiting microwave reflector antenna technology is related to that of solar power generating satellite transmitting antennae, and could become a major sub-system of a lunar power system.

- Microwave power propulsion

High-power microwave beam transmission and reception technologies could be used for microwave-powered propulsion, both in space and for launch. Earth-based microwave-beam propulsion systems are under research today, as they could greatly reduce the amount of propellants needed to be carried on board launch vehicles. Delivering the microwave beams used for launch propulsion from space could greatly reduce the energy that needed to be supplied from Earth, both for constructing space-based power systems and for other purposes, thereby improving the energy payback-time.

- Synergy with wind power

Linked operation of solar and wind power systems has been much studied, since in many places wind energy and insolation are statistically anti-correlated. Combined systems can therefore achieve higher reliability of output, and reduce the need for storage capacity to achieve a given level of reliability. Adding a rectenna to such a combined system would further improve the reliability of their output, thereby further reducing the need for storage.

The term "intelligent grid" has come to be used to describe future electricity networks capable of reliably integrating various forms of terrestrial solar power, wind power, space-based solar power, large-scale power storage systems, and long-distance transmission links to different time-zones. 2030 may be a reasonable date to assume the existence of such a system within Europe. The availability of dependable power supplies from space-based systems would facilitate the integration of large amounts of power delivered by terrestrial power systems on a time-varying basis.

- Extreme weather amelioration

Another application of space-based microwave power transmission technology under investigation is weakening the force of typhoons, hurricanes, cold spells and other extreme weather conditions. Although weather modification raises legal and liability problems that would need to be resolved, some estimates of future global warming predict a substantial increase in extreme weather conditions on Earth. Consequently the ability to ameliorate extreme weather events could be of great economic value, due to the very costly damage, up to tens of billions of Euro, that even a single severe storm, heat-wave or flood can cause. From a technical point of view this application is closer than microwave propulsion to the capability of a solar power satellite, since power delivery targets would be several kilometers in diameter rather than the size of a space vehicle. A technology assessment to learn whether dangerous weather conditions can be influenced beneficially, controllably and in a socially acceptable way would be critical.

b) Synergies with other commercial space activities

NASA's "Fresh Look" study [NASA 1997] estimated that, at a traffic rate of 130,000 tons/year, reusable launch vehicles would be capable of carrying 11 ton payloads to low Earth orbit (LEO) at a cost of $\$121/kg_{payload}$. In 1994 the final report of the "Commercial Space Transportation Study" (CSTS), funded by NASA, concluded that a range of new commercial markets would grow rapidly once launch costs to LEO fell below $\$1,000/kg_{payload}$ [CSTS 1994]. Subsequently the "Analysis of Space Concepts Enabled by New Transportation" (ASCENT) study, funded by NASA Marshall Space Flight Center during 2002, analyzed a range of potential launch markets, and also concluded that once launch costs fell below about $\$1,000/kg_{payload}$ demand would grow rapidly, on a shorter time-scale than that required to develop space-based power systems [Futron 2003].

The growth of these activities, which are expected to be mainly commercial rather than governmental, could make an important contribution to the potential value of developing the low-cost launch system needed to realize space-based solar power supply. Such developments would have economic value in themselves, particularly at the present time of exceptionally high unemployment, both in Europe and elsewhere, due to the relative lack of new industries to offset losses of jobs in maturer industries. They would also reduce the share of launch system development costs that should be attributed to space-based solar power, thereby making its development relatively more attractive.

c) Policy synergies

The relative attractiveness of solar power utilization, both terrestrial and space-based, is influenced by a range of policies, notably including energy policy and environmental policy. However, these technologies also have important synergies with economic policy, foreign policy and industrial policy, which are discussed briefly next.

- European economic policy

At the macro-economic level, Europe is self-sufficient in agriculture, and has a trade surplus in manufactured goods and services which pay for net imports of energy: the countries of the EU import some 500 Mto_e/year [IAEA 2002]. However, imports of manufactured goods from countries with lower costs are growing rapidly, and so Europe has a strategic need to develop new industries which could become a large-scale source of net exports. The roughly 10% unemployment in Germany, France and Italy is a consequence of the difficulty these countries have in developing new industries. Consequently, for Europe to develop a new industry which enabled it to become self-sufficient, or even a net energy exporter, would have great value both economically and strategically.

Energy policy and economic policy (as well as industrial policy, environmental policy and foreign relations) are not the responsibility of ESA nor of the space industry. However, the development of energy independence and even net export capability could have a large influence on all of these different aspects of EU policy. Consequently evaluation of the potential of both terrestrial and space-based solar power from these wider perspectives is desirable. The recent start of formal collaboration between the EU and ESA has created the opportunity for collaborative work to include assessment of space-based power supply from the macro-economic and strategic points of view.

There is a wide gap between the roughly 0.5 trillion Euro which have been spent in Europe on nuclear fission power R&D, the roughly 100 billion Euro that Europe has spent on nuclear fusion and fast-breeder reactor R&D, and the hundreds of millions of Euro that have been spent on terrestrial solar power, versus the few million Euro that have been spent on space-based solar power supply research. This gap is not based on objective comparison of the future potential of these energy sources. It seems to be due more to the institutionally anomalous position of space-based solar power supply which is not supported by those responsible for these fields of EU policy, despite the fact that its development could have important implications for them. For example, the identification of some 20 potential candidate sites for offshore rectennae in Europe in [Bresters 1980] is of interest from the point of view of European energy independence; further study of this subject could be appropriate for ESA/EU collaboration.

If space-based solar power systems were developed as a major new energy source, substantial participation by European companies could be of great value to the EU from the point of view of its concern for long-term economic stability and energy security. For European companies to export energy (e.g. by building solar power satellites and selling microwave power to other countries operating rectennae) is economically equivalent to reducing energy imports. This possibility could also be important for global sustainable development, since global electricity demand is predicted to grow to 20 times that of Europe. However, in view of the rapid progress being made in space technology by both India and China, there is probably not a very long "time-window" during which European aerospace and non-aerospace companies could establish a significant competitive advantage in this field before they will be matched or overtaken by lower-cost countries. For example, the UK DTI conducted a survey of UK companies in 1979 to analyse the industrial capacity and value of SPS manufacture. A large number of non-aerospace companies were included in this survey.

- Environmental policy

Innovations in environmental regulations can cause major changes in the demand-supply conditions of different electricity supply options. In the following, three possible policy initiatives which could greatly affect the development of solar power, both terrestrial and space-based, are briefly considered.

a) Green electricity option

The introduction in recent years of "Green Electricity" options in some countries and districts has enabled customers to express their preference for different forms of electricity generation for the first time. The considerable popular interest in reducing the danger of global warming has led to rapid growth of demand for wind-generated and solar-generated electricity. If this innovation were to spread throughout Europe (and elsewhere) it could lead to accelerated growth of demand for solar electricity generation.

b) Electricity supply re-regulation

Introduction of regulations adjusting electricity supply companies' profit margins according to the average efficiency of their customers' electricity utilization has been shown to be effective in overcoming a serious flaw in financial markets. Under "normal" market conditions, borrowing to invest in increasing electricity supply is much cheaper than borrowing to invest in reducing demand through raising efficiency, due to the greater credit-worthiness of electricity companies than private citizens. Widespread introduction of regulations to correct this market-flaw could substantially alter the patterns of supply and demand for electricity over coming decades. However, raising the efficiency of electricity use in this and other ways is not expected to prevent the growth of global electricity demand by several hundred percent through the 21st century [Hoffert 2002].

c) Environmental taxes

Plans to introduce various forms of pollution taxes, such as a "carbon tax", the "externality surcharge" of up to 15 cents/kWh considered in the Fresh Look Study, and/or "tax-shifting" (i.e. simultaneous increases in environmental taxes in parallel with reductions in other taxes, such as employment taxes) are increasingly being considered in many countries. Progress in this direction would make investment in non-CO_2 producing energy sources, including terrestrial and space-based solar power, more economically attractive.

8.2.6 Conclusions and recommendations from space perspective

A future energy system in which terrestrial solar power played a major role would offer considerable potential for synergy with rectennae.

The combined use of terrestrial SOT systems would require rectennae to be operated with low load-factors, of some 27%. In order for this to be economically competitive, non-base load rectennae would need to receive power from satellites operated at high load factors. The scope for achieving these "network synergies" would increase in larger systems of 100 GW - 500 GW.

Combined use of space-based systems with terrestrial PV systems would enable rectennae to achieve much higher load-factors of some 92%, at which the LEC of space-based power is low, even without network synergies. This possibility could greatly reduce the land area needed, due to rectennae' much higher average power output per unit of land area. Development of space-based solar power systems would be likely to have synergies for the production of PV systems, which could benefit terrestrial PV systems, such as joint technology development and material supply for PV production.

Further analysis of the potential for flexible operation of rectennae, including computer simulation of the operation of networks of multiple satellites and rectennae, could help to clarify the extent of potential synergies with terrestrial solar power and other energy supply systems. Forecasts through 2030 of seasonal electricity demand patterns in Europe and in countries to the east, west and south of Europe, and on daily electricity demand patterns for electricity grids and major cities on both coasts of the Atlantic, would be useful for this.

In order to have the option of large-scale space-based solar power supply on a timely basis – e.g. 100 GW by 2030 – work would need to begin on a range of subjects which lie on the critical path. In the case of space-based solar power, development of a reusable launch system capable of low costs on high rates of traffic is on the critical path. Work towards planning a 10 MW LEO pilot plant, to which the ongoing Kourou-Soyuz facility development may be a key contribution, is also on the critical path. Microwave power transmission technology development, including studies of rectenna design and siting in Europe are also on the critical path to deciding an optimal system design for Europe.

8.3 Further synergies

In the scenarios assessed in the framework of this study it showed up that the costs for energy storage for terrestrial solar power systems are high. Energy storage should thus be avoided as far as possible. To diminish the requirement for energy storage, solar power is fed directly into the grid at times when supply and demand may allow this. During the left time, solar power could be used to produce hydrogen. One can imagine that in future, decentralized electrolyzing facilities are jointly controlled by means of a virtual load on the one hand and decentralized renewable generation systems are jointly controlled by means of a virtual power plant on the other hand. Furthermore, in order to gain comparison results within a reasonable timeframe for this study, the scenario design was limited to a single terrestrial source of renewable energy (notably photovoltaics and solar thermal respectively). These aspects are discussed briefly in an excursus in chapter 8.3.1 (REG-MIX).

This study focused on electricity demand only. Yet, for 2030 a significant demand for hydrogen would have to be considered too as an potential target market for renewable energy. A tour d'horizon is given in chapter 8.3.2 (H2-OPTION) on this issue including potential advantages that may arise from the hydrogen option.

Alternative operational modes for space-based solar power systems are discussed in chapter 8.3.3 such as the alternating supply of countries which are beyond the geographical scope of this study.

8.3.1 European renewable electricity mix (REG-MIX)

In the scenarios discussed throughout this study a very high share of the electricity generated by the terrestrial solar power plants has to be stored to compensate fluctuations. But these scenarios are not realistic. Up to relatively high shares of fluctuating electricity can easily be absorbed from the grid (the critical share is when the installed nominal capacity of fluctuating renewable power plants exceeds the scheduled power demand, then excess energy would have to be dumped). As a result no storage would be required for the inclusion of relatively small amounts of fluctuating electricity supply.

Furthermore, it is a simplification for the purpose of this study to use only a single renewable energy source. In reality there is always a mix of different renewable energy sources. PV plants generate large amounts of electricity during summer days whereas wind power stations have their highest electricity output in winter. As a result fluctuations are compensated at a large extent by the mixture of different renewable energy sources. Therefore in the following subchapters the influence of a mixture of different renewable electricity sources on the requirement of electricity storage capacity is discussed.

The relatively high share of base load electricity in the UCTE grid is theoretical and does not represent the local situation in the grid. The fluctuations of the local electricity demand is far higher than the fluctuations of the overall UCTE grid. Therefore electricity demand fluctuations would actually have to be handled which are greater than assumed in this study.

a) Overview renewable energies

This subchapter gives an overview over major typical renewable energies in Europe which could make substantial contributions to the European energy demand in future.

- Wind

In some European countries (e.g. Germany, Spain) the cumulative installed wind electricity generation is growing at a high pace (Figure 8-10). Meanwhile, the installed wind power capacity in Germany is capable to meet about 5% of the total electricity demand.

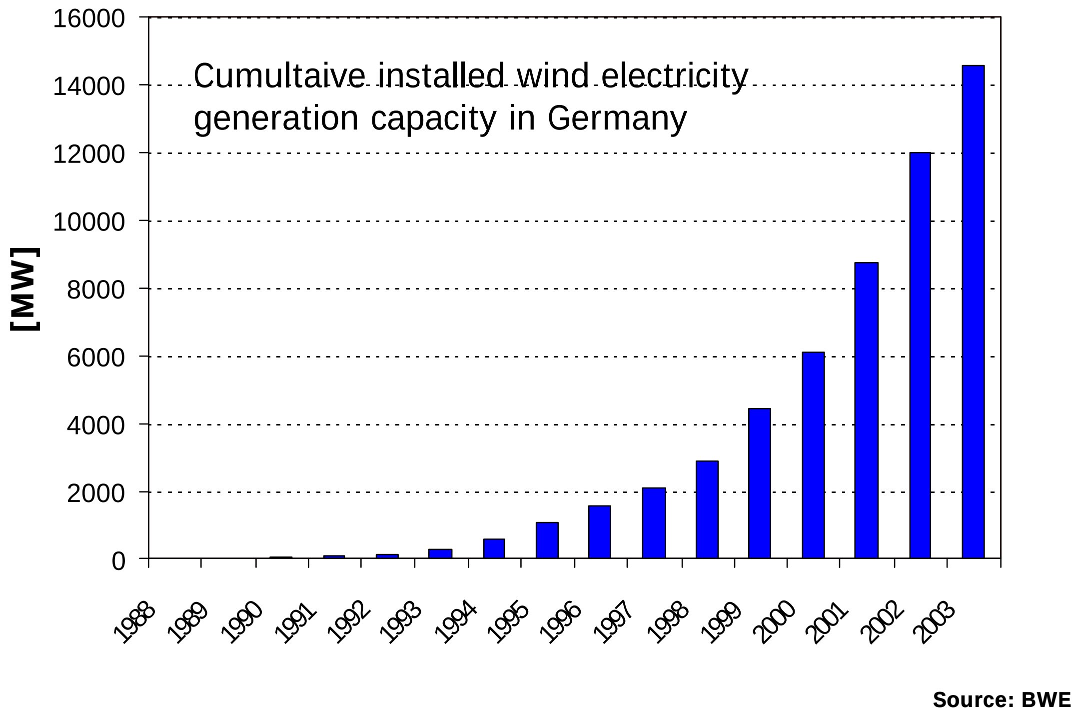

Figure 8-10: Cumulative installed wind electricity generation capacity in Germany

By end of 2003 some 28,440 MW of wind power are installed in the EU generating about 2.4% of the electricity consumption of EU-15 [EWEA 2004]. The European Wind Energy Association (EWEA) sets the target for the installation of onshore wind power in the EU-15 at 65,000 MW by 2010 and 110,000 MW by 2020 and for the installation of offshore wind power at 10,000 MW by 2010 and 70,000 MW by 2020. Thus, the total installed wind power capacity would reach about 75,000 by 2010 and 180,000 by 2020 [EWEA 2003].

In [Van Wijk 1994] the potential for electricity generation from wind power in OECD Europe is indicated with some 850 TWh per year. For the calculation areas with average wind speeds below 5.1 m/s (at a height of 50 m above the ground) were excluded as well as inaccessible areas such as mountains, arctic or dessert areas. Finally, it was assumed that 4% of the remaining area is available for wind power installations. The potential indicated in [Van Wijk 1994] can thus be considered as a conservative estimate as can be seen in Germany: [Van Wijk 1994] indicated the potential for Germany with some 24 TWh per year. This was already been reached by the end of 2003[9] and wind electricity generation capacity in Germany is continuously growing.

In [Van Wijk 1994] only OECD Europe were considered but not the eastward enlargement of the EU with states such as Poland, Czech Republic etc. The inclusion of these states will increase the potential for electricity from onshore installed wind power within Europe to probably more than 1,000 TWh per year.

Furthermore, there is a large potential for offshore wind power installations in Europe which was not yet considered by [Van Wijk 1994]. The total offshore wind energy potential for Europe is estimated at between 550 and 3,000 TWh/yr of electricity depending on the maximum allowable water depth and the maximum distance from the coast [Joule 1995] (Table 8-14). The upper value represents more than the equivalent of the total annual electricity consumption of EU-15. In 2000 the electricity consumption within the EU-15 was approximately 2,570 TWh [IEA 2002].

Wate depth [m]	Distance from land [km]		
	0-10 [TWh/yr]	10-20 [TWh/yr]	20-30 [TWh/yr]
10	551	587	596
20	1121	1402	1523
30	1597	2192	2463
40	1852	2615	3028

Table 8-14: Potential offshore wind electricity capacity in EU-15; the upper and lower boundaries are indicated in yellow [Joule 1995]

The distance between the coast and the offshore wind field "Utgrunden" in Sweden (7 wind converters, each 1.5 MW) is about 12.5 km and the water depth ranges between 7.2 and 9.8 m. The distance between the coast and the offshore wind field "Horns Rev" in Denmark (80 wind converters, each 2 MW) ranges between 14 and 20 km whereas the water depth varies between 6 to 14 m. The planned offshore wind field "Butendiek" will be located at the North Sea, some 34 km off the German island Sylt. The water depth will be between 17 and 20 m. "Butendiek" will be in operation by the end of 2006. Therefore

[9] Installed capacity at the end of 2003 in Germany: 14.6 GW; average electricity yield: 1,800 GWh per GW of installed capacity

it can be concluded that the upper value for the potential for electricity from offshore wind power is realistic.

All in all approximately 4,000 TWh of electricity could be generated by wind power within Europe including Turkey (thereof 1,000 TWh onshore and 3,000 TWh offshore). According to [Eurelectric 2001] estimations for 2020 the total electricity consumption of EU-25 including Bulgaria, Norway, Romania, Switzerland and Turkey is some 4,500 TWh.

By the end of 2003 an offshore wind power capacity of some 560 MW has already been installed within EU-15 which generates about 2 TWh electricity annually. The total installed wind power capacity has reached some 28,440 in 2003.

	Total [MW]	**Thereof offshore [MW]**
Austria	415	-
France	239	0
Finland	51	0
Germany	14,609	0
Greece	375	0
Denmark	3,110	425
Sweden	399	23
United Kingdom	649	64
Ireland	186	25
Italy	904	0
Luxembourg	22	0
The Netherlands	912	19
Belgium	68	0
Portugal	299	0
Spain	6202	0
Total	28,440	557

Table 8-15: Installed wind power capacity in the EU-15 in end 2003 [EWEA 2004], [WSH 2004]

By now most of wind power is installed in selected countries of the EU-15. But the installed wind power capacity also increases in other European countries (Figure 8-11).

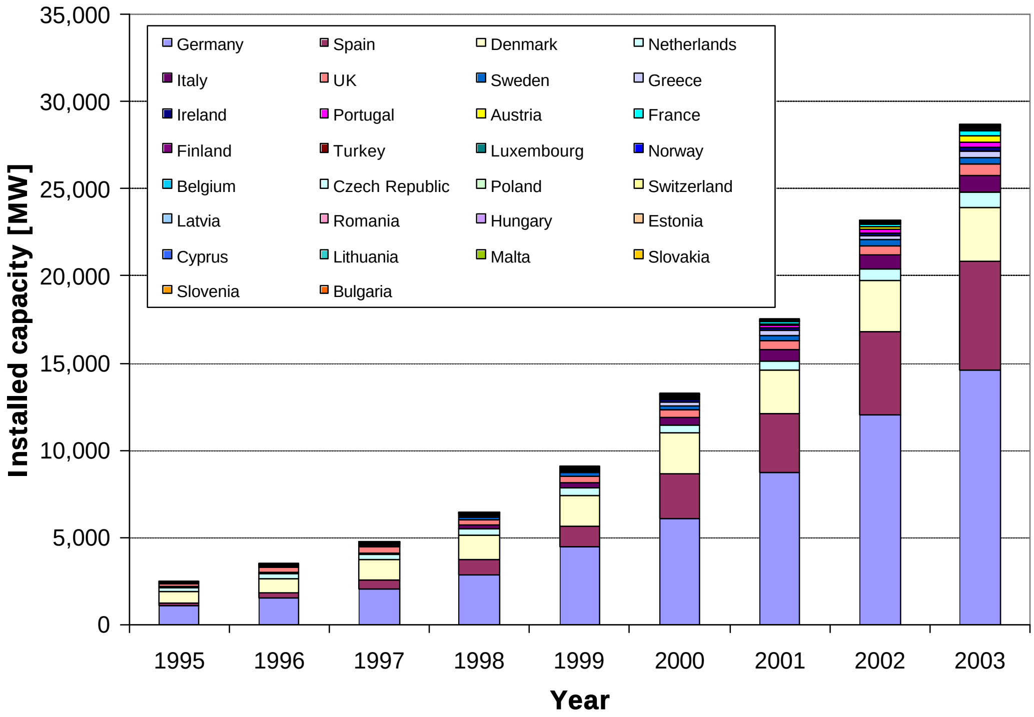

Figure 8-11: Installed wind power capacity in different European countries [BWE 2003], [EWEA 2004], [Wind Power Monthly 2004]

For the integration of wind power into the electricity grid a forecast of available wind power for at least the next 15 minutes up to 4 hours is crucial for grid-stability, especially when wind power is connected to a grid with significant amounts of base load power generation capacities, such as coal and nuclear power stations. Meanwhile wind power forecast models have been developed with a forecast error of only 8.8% for a 24h advance-forecast. For forecasts of 2 – 8 hours in advance, the forecast error is at some 6% [ISET 2003].

- Biomass

Biomass can be distinguished in lignocellulosic biomass – such as wood chips – and biogas which is derived from fermentation processes. Lignocellulosic products can be utilized via combustion in steam turbine power plants, and via gasification in downstream gas engines, gas turbines or combined cycle gas turbines. Biogas can be applied in gas engines or in small gas turbines.

Biomass feedstock can be derived from residues and from dedicated plantation of energy crops.

	Biomass [1)] **[EJ/yr]**	h_e **[%]**	**Electricity [TWh/yr]**
Residual woody biomass (thereof EU-15)	4.0 (3.0)	25 [1)]	278 (208)
Residual Straw (thereof EU-15)	1.6 (1.0)	25 [1)]	111 (69)
Biogas from agriculture residue	0.3	33	28
Plantation (thereof EU-15)	2.6 (1.4)	25 [1)]	181 (97)
Total (thereof EU)	8.5 (5.4)	-	598 (374)

[1)] [Kaltschmitt 2001]; [2)] besides electricity heat is co-generated for district heating

Table 8-16: Electricity generation potential from biomass in Europe (without former USSR)

From the potentials shown in Table 8-16 some 2 EJ (≈ 25% of the potential) is already used for heat and electricity generation. In several countries (e.g. Austria, Germany, Sweden) the number of biomass fueled heat and electricity generation plants increases at a high pace (heating plants, co-generation, pellets fueled heater). The potential for biogas in Table 8-16 is not complete (only biogas from manure is shown). Biogas also can be derived from sludge e.g. from water purification plants and can also be generated from organic waste e.g. from households and catering and from the plantation of grasses. The electricity generation capacity of biogas plants has increased in several countries (e.g. biogas plants in Germany, see Figure 8-12).

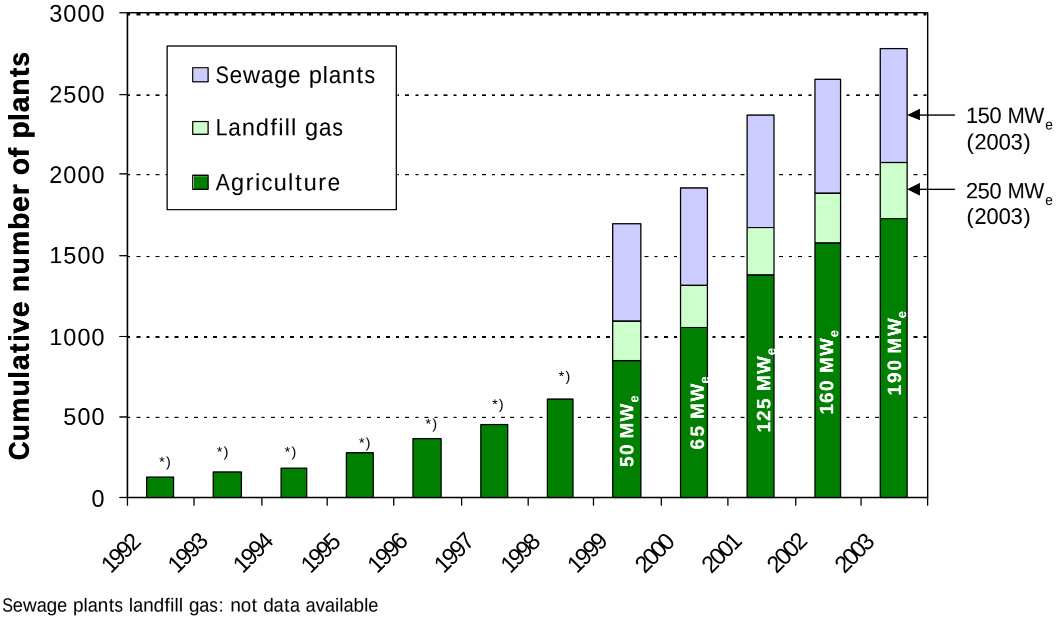

Figure 8-12: Installed capacity of biogas plants in Germany [BWK 4/2004], [Jahrbuch EE 2003]

E.g. in 2003 in Germany the electricity generation from biogas plants using agricultural residues as feedstock were some 1.2 TWh, from biogas plants using landfill gas some 1.1 TWh and from biogas plants installed at sewage plants some 0.8 TWh.

- Geothermal

So far most of the geothermal power plants are located in regions with active volcanoes. The accessible geothermal electricity potential in regions with active volcanoes in Europe including the Commonwealth of Independant States (CIS) and Turkey is estimated with some 2,030 TWh_{el}/yr based on a sustainable electricity generation[10] [Bjornsson 1998].

But geothermal energy sources are also located in region with no active volcanoes. There, the temperature level is relatively low (< 180°C). With Organic Rankine Cycle (ORC) or the Kalina Cycle these geothermal sources with relative low temperatures (100 to 180°C) can be used for power generation. Several ORC plants are already in operation (e.g. in

[10] In many literature sources the potential of these geothermal sources is not related to sustainable use but only related to a certain period of time (e.g. 1,000 years of operation).

Altheim / Austria, Neustadt-Glewe in Mecklenburg-Western Pomerania / Germany) or are under construction (e.g. in Unterhaching nearby Munich / Germany).

- Hydro

In [LTI 1998] the potential for electricity generation from hydro power within the EU-15 is indicated with some 489 TWh/yr, thereof about 270 TWh were already in production in 1990. The ecologically acceptable extension of hydro power in Europe is assumed mainly in the field of small installations of < 10 MW of which so far only 20% to 25% have been exploited [LTI 1998]. Furthermore, it is assumed that 90% of this unused potential will be exploited until 2050 thus reaching an electric output of 441 TWh [11] per year including the capacity of larger power plants > 10 MW already built. Furthermore, additional hydro power capacity is achieved by converting some hydro power plants to storage power stations which would result in additional electric power output of about 29 TWh [12] per year. As a result an ecologically acceptable extension up to 470 TWh/yr is possible (technical potential: 481 TWh/yr).

[Grubb 1997] estimates the potential of additional hydro power plants which can be added to the hydro power plants already in operation at some 138 TWh/yr (< 10 MW_e) and some 73 TWh/yr (> 10 MW_{el}) based on hydro power plants in operation in 1994 (large scale hydro power: 292.5 TWh; small scale hydro power: 24.6 TWh). In case of the small hydro power plants some 3,400 annual full load hours were assumed by [Grubb 1997]. Based on the electricity generated from hydro power in 1994 (317 TWh) the technical potential would be some 528 TWh/yr.

In 2000 about 319 TWh of electric power were generated by hydro power within the EU-15 [IEA 2002]. As a result the potential of additional hydro power is about 150 TWh/yr based on the technical and ecologically acceptable extension of some 470 TWh/yr without considering a new hydropower concepts, such as wave-power.

In Europe, there is a large wave energy potential especially in Ireland, Portugal, Norway and United Kingdom. The EU member states Ireland, Portugal and United Kingdom represent a theoretical overall wave energy capacity potential of some 130 GW based on 8760 annual full load hours [Petroncini 2000] which would represent some 1,140 TWh per year. Assumed that 10% of the theoretical potential can be developed about 114 TWh per year could be generated by wave power in these three countries.

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[11] In [LTI 1998], the specific average capacities are given e.g. hydro power: 137 W/capita. The "average capacity" is related to 8,760 operating hours per year and to the population in the EU (about 367.4 millions).

[12] Average capacity: 9 W/capita

b) Market introduction

According to EU Directive 2001/77/EC the share of renewable electricity sources in the EU-25 should be at least 21% until 2010. This target will not be met automatically.

Renewable energies face a chicken and egg problem. Though the running costs of renewable energy are generally low (especially with renewable energy systems which do not require some kind of fuel, such as wind, PV etc.), current investment costs are relatively high which is a significant hurdle on the route to commercialization. In grid-connected applications the overall cost of power generation is still usually higher with renewable energies compared to conventional means of power generation.

In the different EU countries there are different concepts to boost the market introduction of renewable energy sources. In some countries a renewable energy certificate system is used. Other countries use fixed feed-in tariffs for renewable electricity.

In UK the renewable's obligation certificates (ROC) is applied. In Italy a similar regulation has been introduced (green certificates). UK aims to rise the renewable energies share of electricity production to 10% by 2010 and 20% by 2020 [New Energy 4/2003].

In the Netherlands a tax exemption for green electricity has prompted more than 1.8 million households to switch to green power since 2001 when the green certificates were introduced. In Italy electricity producers or importers with more than 100 GWh per year net of co-generation have been under orders to generate at least 2% of their net sales from renewable energy sources or to buy the equivalent amount in green certificates [New Energy 4/2003].

In Denmark, a green certificate market was planned to start early 2000 and to be operating by 2003. Due to strong oppositions, implementation of the scheme has been delayed and details are being revised. Before the planned introduction of the green certificate market operators of renewable power stations received a fixed feed-in tariff [New Energy 4/2003].

In Austria, France, Germany and Spain the grid operators has to pay a fixed compensation for electricity from renewable energy sources (fixed feed-in tariff system). France introduced the fixed feed-in tariff in 2001 and Austria in 2002. The German government aims to raise the share of renewable electricity to at least 12.5% by 2010 and to at least 20% to 2020.

The fixed feed-in tariff system has resulted to be the most successful tool for market introduction renewable energy sources. E.g. in Germany, Spain and Austria more than 75% of the wind power capacity within the EU-15 has been installed.

c) Renewable mix scenarios in other studies

In [Quaschning 2000] the combination of different renewable energy sources for a complete renewable electricity supply in Germany has been investigated.

The total wind electricity generation capacity has been assumed to be 77.1 GW (midland: 31.8 GW; highland: 5.9 GW; near coastal land: 12.5 GW; coastal land: 3.3 GW; offshore: 23.6 GW). The total photovoltaic capacity has been assumed to be 202.9 GW (roofs: 129.5 GW; facades: 30 GW; noise barriers: 5.9 GW; other land: 37.5 GW). Further biomass (e.g. wood chips) and biogas plants and hydropower are assumed in the scenario. For electricity storage hydrogen and existing pumped hydro power plants were applied (Table 8-17). Further it is assumed that the electricity consumption decreases because of electricity saving efforts.

	Capacity [GW_e]	**Electricity generation [TWh/yr]**
Photovoltaic (PV)	202.9	175
Wind (onshore)	53.5	85.3
Wind (offshore)	23.6	78.6
Hydro		24.7
Biomass (residue)	11	33
Biomass (plantation)	5.7	17
Total		**413.6**

Table 8-17: Electricity generation capacity and electricity generation in a scenario for a complete renewable electricity supply in Germany [Quaschning 1999], [Quaschning 2000]

Short time fluctuations from fluctuating renewable energy sources such as wind power and photovoltaic electricity can be bridged by pumped hydro and the inclusion of renewable energy sources such as biomass and biogas. Biomass and biogas plants are partly used for the supply of balance energy. Furthermore, fluctuations can be eased by demand side energy management. E.g. heat pumps can be powered by excess wind electricity because heat can easily be stored for several hours up to several days.

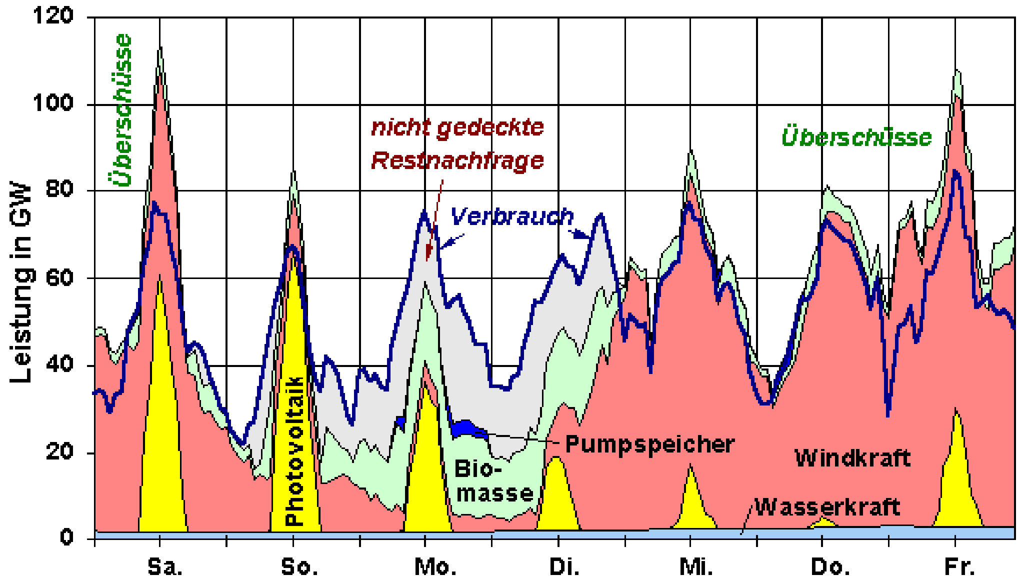


Figure 8-13: Electricity generation of the different electricity sources in a complete renewable electricity supply scenario for Germany during typical week in December

Figure 8-14 shows the average monthly electricity generation in a complete renewable electricity supply scenario for Germany for the case when 60% of the photovoltaic electricity (60% of 175 TWh/yr) is replaced by imported electricity from solar power stations located in Southern Europe and North Africa.

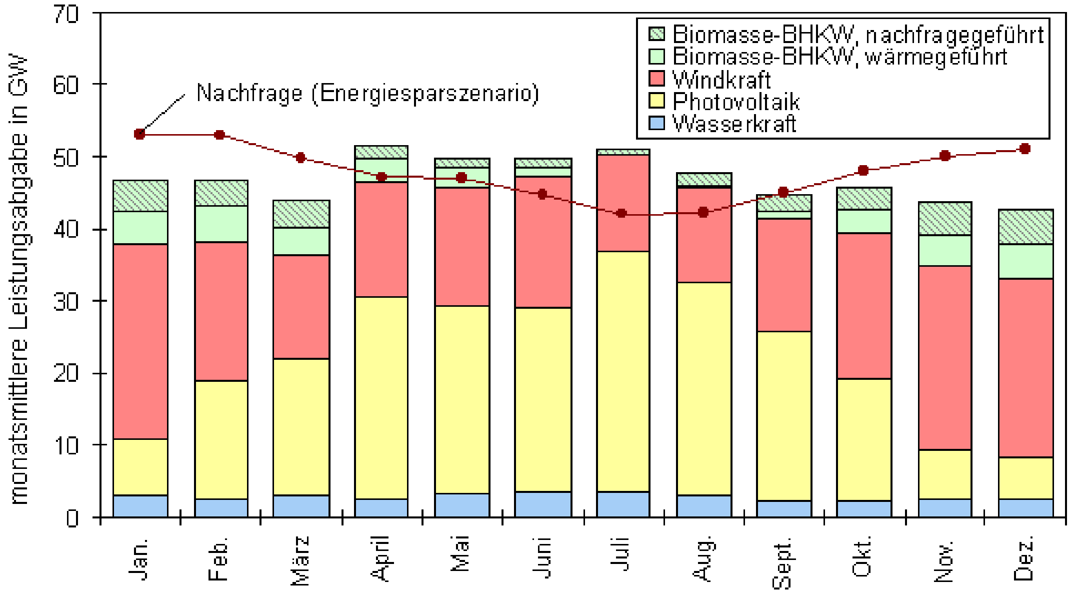


Figure 8-14: Electricity supply from different renewable energy sources for the different month in a fully renewable electricity supply scenario for Germany [Qaschning 1999]

As a result the combination of the different renewable electricity sources in a complete renewable electricity supply scenario for Germany could result in electricity storage requirements as low as 3% of installed storage capacity [Quaschning 2000].

The scenario discribes a best case regarding electricity storage demand. If demand side energy management was assumed not to be applicable at the extent as described in [Quaschning 2000] the resulting electricity storage requirements would be higher.

On the other hand, the introduction of hydrogen could facilitate the inclusion of fluctuating electricity sources into the grid. Excess electricity from wind or photovoltaic power plants could generate hydrogen e.g. transportation purposes either onsite at the filling station or in central electrolyzing facilities.

d) Energy efficiency improvements and changing consumer behaviors

As already assumed for WP1 and WP2, power demand in the different countries within the EU 2030 will probably assimilate.

Energy savings can accelerate the share of renewable towards a 100% renewable electricity supply. In several countries e.g. France, Sweden and Norway a rather large share of electricity is used for heating of residential and commercial buildings. If the direct electricity heating was replaced by heating pumps the electricity consumption would drop significantly by at least a factor of two, in most cases of a factor of three, and in some cases even more.

In southern countries solar thermal collectors combined with absorption technology can be used for cooling purposes e.g. for air conditioning instead of electrically driven air conditioners.

The reduction of absolute power demand might occur together with the shifting of peak power phases which lead to a modification of power demand curve.

e) Conclusion

The potential of renewable energy sources can meet the electricity demand of Europe even without considering imports of renewable electricity from North Africa. There would even remain some potential for hydrogen production in order to partly meet the demand of clean transportation fuels in future.

Electricity savings (e.g. replacement of directly electrically heating of residential and commercial buildings by heat pumps) can reduce the electricity consumption significantly. Then a 100% renewable electricity supply can be reached within a shorter time. Further the potential for the replacement of fossil transportation would then be elevated.

Including the potential of renewable energy sources in North Africa and including considering the energy demand of the inhabitants of North Africa, terrestrial renewable energy sources would be sufficient to fully meet the electricity demand for both stationary applications and for the production of hydrogen to replace fossil transportation fuels.

Electricity from wind power and biomass will reach significant shares of the European electricity supply within the next 10 to 20 years.

Fluctuations of renewable electricity supply from fluctuating energy sources such as wind power and solar power can be compensated to a large extent by combination of different renewable electricity sources. Demand side energy management can reduce the requirement for electricity storage further.

8.3.2 Hydrogen option (H_2-OPTION)

The introduction of hydrogen as secondary energy carrier for transportation and other purposes can decrease the electricity storage demand for stationary electricity use. Hydrogen can be generated when excess electricity e.g. from fluctuating renewable energy sources such as wind and solar power occur. Filling stations with onsite electrolyzers would be operated with surplus electricity. Furthermore, electricity from offshore rectennae or large offshore wind power installations can be used for central hydrogen production to avoid the construction of additional electricity transmission lines.

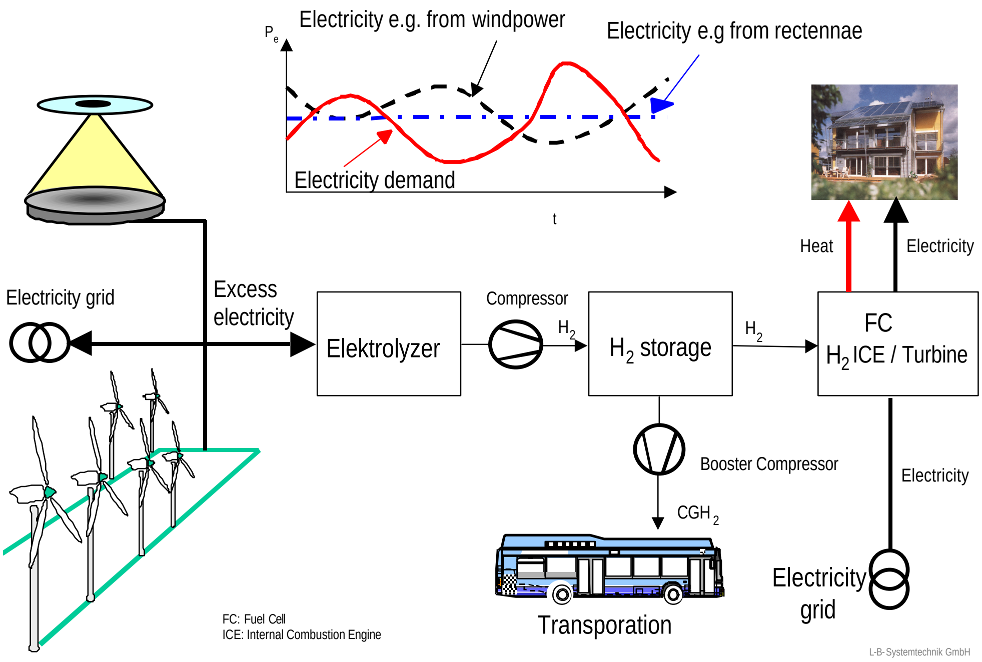


Figure 8-15: Hydrogen from excess electricity such as from wind farms or rectennae for transportation purposes and stationary power generation (LBST)

The most efficient and economic way of hydrogen utilitzation is for transportation purposes as well as for combined heat and power generation for stationary power and heat supply purposes. Whenever possible, hydrogen re-electrification for power generation purposes should be avoided as far as possible in favor of direct electricity use. However, hydrogen produced from excess electricity offers cost advantages and potential synergies between different applications and markets.

a) Hydrogen applications and markets

A broad range of established markets could be positively affected by the introduction of hydrogen and fuel cells. Without being exhaustive, some of these applications and markets are depicted in Figure 8-16.

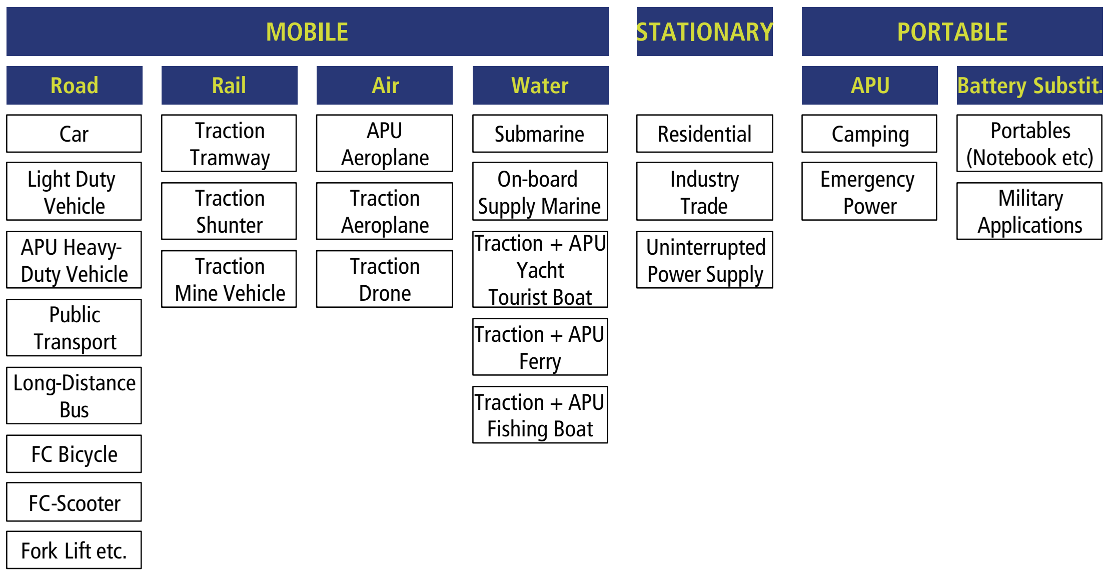


Figure 8-16: Potential hydrogen applications (LBST)

So far, in the framework of this study the focus was put on the electricity market as target market. However, hydrogen as an energy carrier for transportation purposes alone is a potentially huge market (see Figure 8-17) which could be supplied, too, e.g. with excess energy.

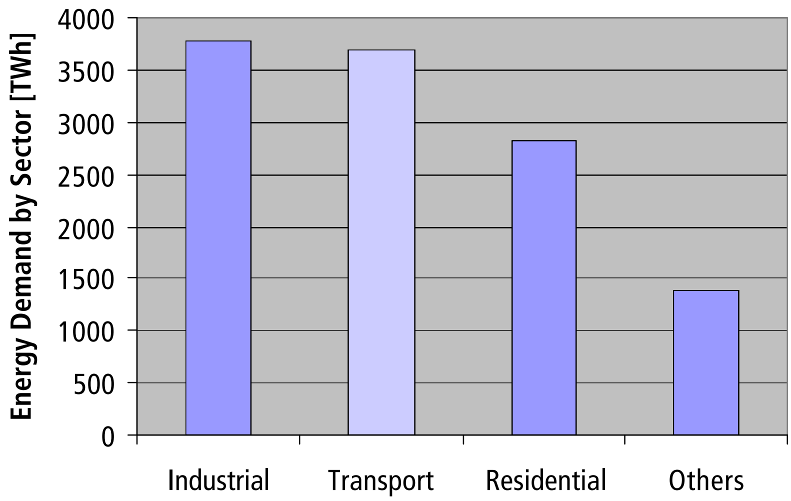


Figure 8-17: Primary energy demand by sector in EU-15 in the year 2000 [IEA 2002]

Today, the transport sector depends strongly on petroleum fuel. Some 98% of the transportation energy is provided by petroleum.

A number of drivers foster the substitution of petroleum fuel:

- Constraints of fossil resources while world demand is rising (see chapter 2.1.4)
- Energy security: Europe's dependency on oil imports from non-European countries
- Environment (local air pollution, climate change): Greenhouse gas emissions in industrialized countries have to be cut by 80% by the year 2050. Though public focus is mostly on power generation and consumption, activities to include the transportation sector started already mid 1995. In 2000 the EU announced to introduce mandatory emission targets for the transportation sector comprising emissions from CO_2, N_2O, Methane, R134a and so called 'F-gases' (HFC, PFC, SF6) analogue to the Kyoto Protocol. The European automotive industry, represented by the European Automobile Manufacturers Association (ACEA), favored a self commitment for CO_2 only over an EU directive which finally became accepted by the EU. The target agreed in the self commitment is a reduction of fleet CO_2 emission of newly built vehicles from current 165 g/km (2003) down to 140 g/km in 2008. The target value corresponds to some 5.8 l/100km gasoline consumption. The European car manufacturers also committed to introduce vehicles with specific CO_2 emissions of 120 g/km or less no later than 2000. [ACEA 2003]
- Integrative and improved technology (broad range of primary fuels, fuel cell applications, energy efficiency)

A number of alternative fuels for propulsion were and are under consideration, such as batteries, biofuels, synthetic fuels and hydrogen. Though the efforts for commercialization and infrastructure development are high, hydrogen is assumed to provide the highest overall benefit and potential for future application for transportation (and stationary) purposes.

Politics and industry have made strong commitments to promote hydrogen for transportation purposes, such as Bush's $1.7 billion programme, financial R&D efforts of some € 2.8 billion from the EU side and a strategic road-map for commercialization in Japan.

b) Hydrogen production

Different production technologies and primary energy sources offer a wide range of potential production pathways for hydrogen. Table 8-18 gives an overview of the different primary energy sources for hydrogen production and supply.

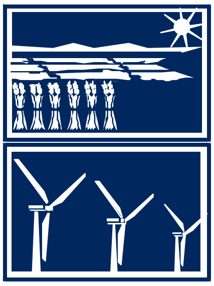
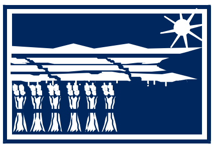
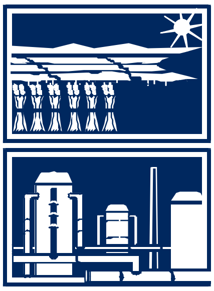
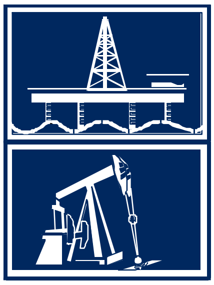
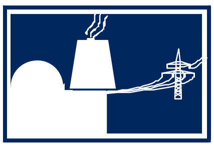
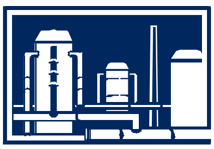
RENEWABLE		Photovoltaik Geothermal Solar Thermal Water Wind
		Biomass Biowaste
		Bacteria Micro-Algae Microbes Synthetic Photosynthesis
FOSSIL		Oil Natural Gas Unconventional Oil Coal
NUCLEAR		Fission Fusion
INDUSTRY		Industrial Hydrogen

Table 8-18: Possible primary energy sources for hydrogen production (LBST)

Figure 8-18 illustrates the various pathways of a hydrogen economy. Most of the technologies depicted in Figure 8-18 are complementing technologies. This gives numerous degrees of freedom for an optimal system design regarding the target application and the locally predominating resource basis.

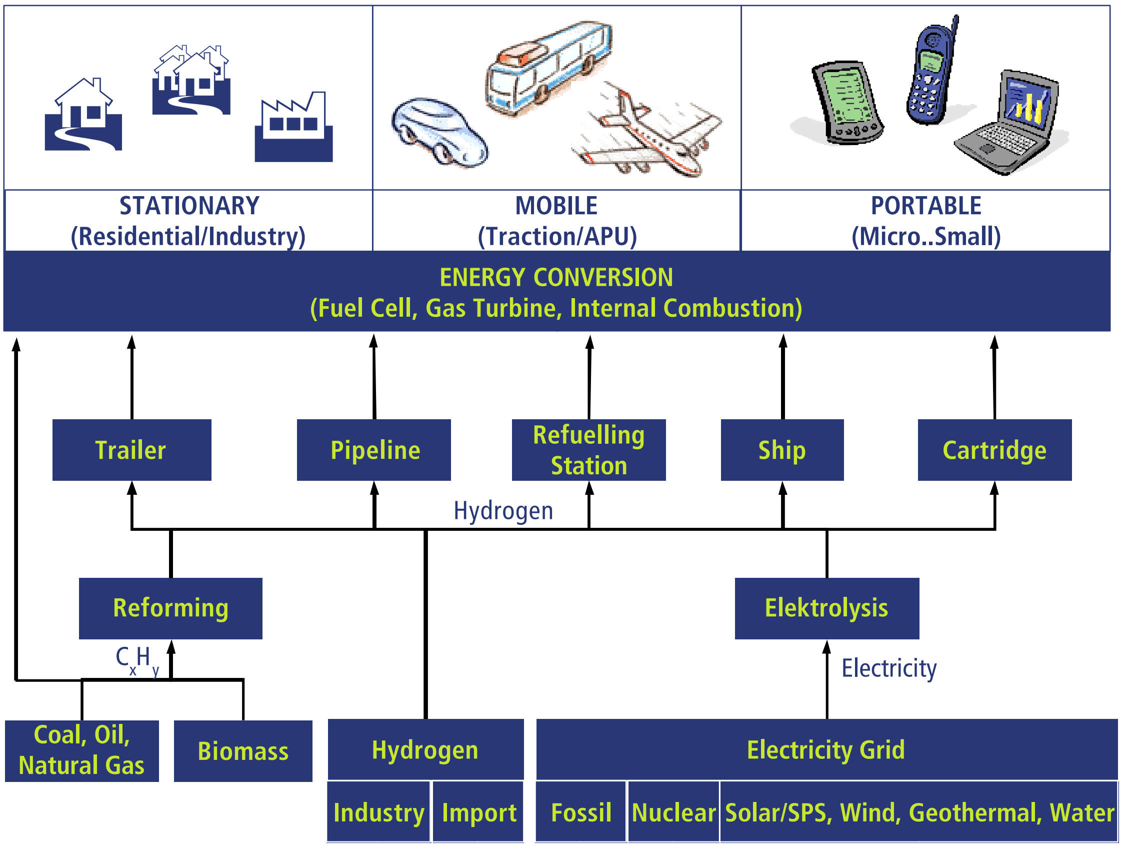


Figure 8-18: Technological pathways of a hydrogen/fuel cell economy (LBST)

During the last couple of years, the automotive and oil industry launched several studies to analyze potential alternative fuels for transportation purposes. These studies came to the conclusion that hydrogen based on renewable energies is the most promising solution in the long-term, e.g. Transport Energy Strategy group (TES) [BMVBW 2001], the California Fuel Cell Partnership [CaFCP 2003] and well-to-wheel analysis of General Motors for the North American and Europen regions [LBST 2002].

As can be seen in Figure 8-19, hydrogen generated by electricity from renewable energy sources such as wind power offers the highest green house gas (GHG) emission reduction potential. Compared to crude oil based fuels i.e. diesel a reduction of GHG emissions up to 100% is possible when compressed gaseous hydrogen (CGH_2) is produced via on-site electrolysis from wind power (or other renewable electricity sources). Other fuels like Fischer Tropsch (FT) diesel derived from natural gas (NG) do not reduce the GHG emission. Further natural gas fuels face analogue problem as oil products: constrains of fossil fuel resources especially crude oil and natural gas and political dependency from suppliers such as Russia. Furthermore, there will be an increasing natural gas demand from emerging economies, such as China. Biomass based fuels such as ethanol are limited by land availability and as a result are in competition with other agriculture use (food production but also the production of renewable raw materials used for insulation material, textiles etc.). Hydrogen can be made from biomass but also can be made from renewable electricity. But the realistic biomass potential available for transport fuels is not sufficient to generate all hydrogen required to meet the future hydrogen demand of the transport sector.

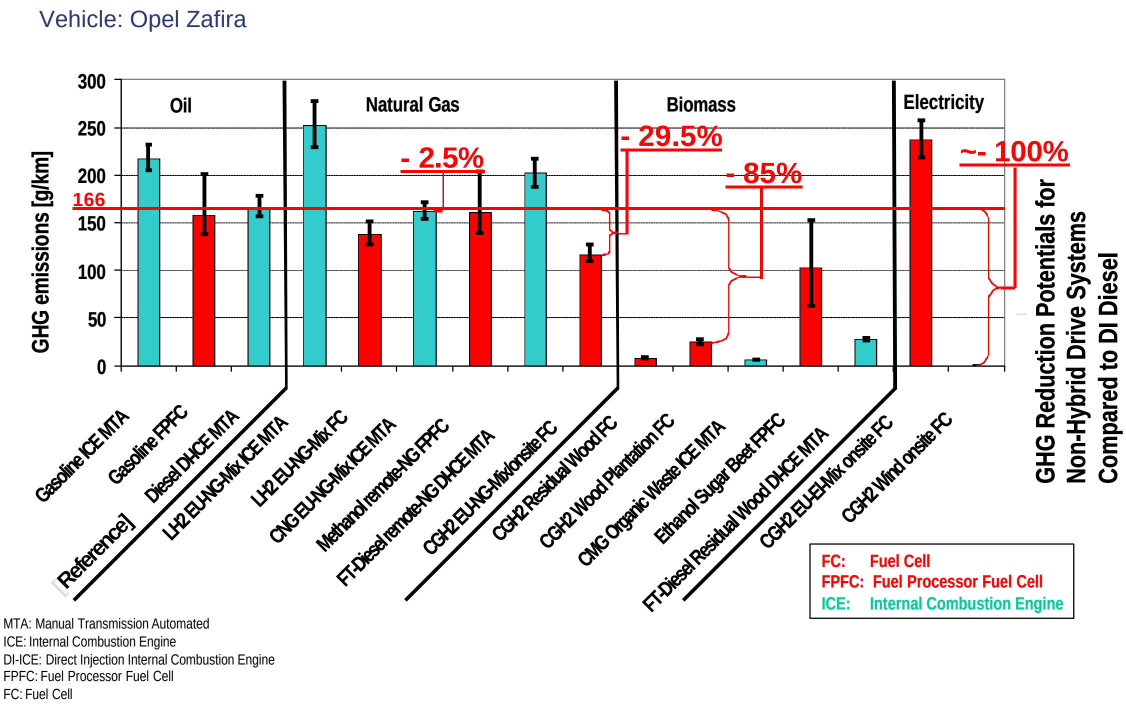


Figure 8-19: Well-to-Wheel analysis of various conventional and renewable fuel paths for automotive application [LBST 2002]

For 2030 the most promising option for alternative transportation fuel is hydrogen produced from renewable energy sources such as solar and wind power.

Assuming that a space-based solar power system ('Solar Disk', GEO stationary position, 7,884 h/yr), would be exclusively operated for hydrogen production purposes, the following number of medium sized cars (each 10,000 km/yr at 50 kWh_{H2_LHV}/100km) could be supplied depending on the different scenario size (Table 8-19). For a first estimation, it is assumed that hydrogen production and consumption take place in closer vicinity to each other so that transportation effort is negligible. It is further assumed that the driving cycle tank-to-wheel efficiency is 40% of the fuel cell powered car. Furthermore, a pressure electrolyzer with an average efficiency of 1.5 kWh_e/kWh_{H2_LHV} and an output pressure of 20 MPa is assumed. Two variants are examined: compression work to 70 MPa with an energy effort of 0.07 kWh_e/kWh_{H2_LHV} and hydrogen liquefaction considering a conventional liquefaction plant with 0.3 kWh_e/kWh_{LH2_LHV} (an advanced optimized liquefaction process could require as low as 0.21 kWh_e/kWh_{LH2_LHV} energy effort in the future).

Scenario size [GW]	No. of cars (CGH_2)	No. of cars (LH_2)
0.5	502,166	438,000
5	5,021,656	4,380,000
10	10,043,312	8,760,000
50	50,216,561	43,800,000
100	100,433,121	87,600,000
150	150,649,682	131,400,000
500	502,165,605	438,000,000

Table 8-19: Numbers of mid-sized cars supplied by an SPS system at various scenario sizes

As a rule of thumb, it can be said that per each GW of installed SPS capacity one million fuel cell powered cars can be supplied on a compressed gas hydrogen basis.

c) Current activities

Hydrogen and fuel cell technologies are high on the European political agenda since October 1992 at the latest. Romano Prodi (president of the European Commission), Phillipe Busquin (EU Commissioner for research) as well as Loyola de Palacio (EU Commissioner for energy and transportation) repeatedly gave a favorable opinion for hydrogen and fuel cell technologies. By then, no dedicated EU programme for hydrogen and fuel cell research existed in the sixth framework programme of the European Union. At that time the USA already pursued their "Hydrogen, Fuel Cells & Infrastructure Technologies Program" (www.fossil.energy.gov/programs/fuels/). Japan skipped their long-bevor WE-NET program for the sake of the "Millennium Project" as well as the "Japan Hydrogen Fuel Cell Demonstration Project (JHFC)".

Mid of June 2003, European commission president Romano Prodi and the US energy minister Spencer Abraham signed an agreement for a joint EU US research in the field of fuel cell technology. Seven focus points were identified therein:

– Field trials in the transportation sector (including transportation infrastructure)
– Fuel cells for auxiliary power units (APU) to be placed in conventional cars
– Standards for fuel infrastructure, vehicles and APUs
– System analyses for fuel supply as well as analyses of material resources for low temperature fuel cells
– Studies in the field including the resource situation of rare earth metals for high-temperature fuel cells
– Direct-methanol (DMFC) and proton exchange membrane fuel cells (PEMFC) for mobile and stationary applications
– Solid-oxide fuel cell (SOFC) as well as hybrid systems comprising high-temperature fuel cells and turbines

Already in the beginning of 2003, the US initiated a world-wide research initiative entitled "International Partnership for the Hydrogen Economy (IPHE)". This initiative followed shortly after US president George W. Bush's State of the Union speech in which he assigned hydrogen a key role for the future energy supply. Meanwhile, all major countries in the field of fuel cell research and development joined the IPHE (Australia, Brazili, Canada, China, France, Germany, Iceland, India, Italy, Japan, Norway, Republic of Korea, Russia, UK, USA and the European Union).

For the following 5 years, the USA will support hydrogen and fuel cell technology development with 1.7 billion US$ in the framework of the FreedomCar programme and the president's initiative.

Mid November 2003, the European Commission presented its action plan to the public. 2.8 billion EUR shall be spent exclusively for hydrogen research, development and demonstration up to the year 2015 in the framework of the Hypogen and Hycom programme.

The car as well as the oil industry have partly strongly committed to hydrogen. General Motors, Daimler Chrysler and Toyota each invested in the order of magnitude of 1 billion EUR in research, development and demonstration so far. Shell founded Shell hydrogen in 1999. BP/ARAL, TOTAL, ChevronTexaco, Exxon Mobil and others are active in infrastructure developments.

Some 110 different prototypes of fuel cell powered vehicles and some 36 different hydrogen vehicles with internal combustion engine (ICE) have been developed since 1967. Of most of these prototypes several exemplars were manufactured. Thus, all in all, some 230 fuel cell and 66 ICE powered vehicles were built as per beginning of the year 2003. Thereof, the absolute majority was produced after 1995.

Figure 8-20: Hydrogen powered fuel cell vehicle based on the 'Zafira' platform by General Motors (Opel); the HydroGen3 was built in two versions: with a liquid and a gaseous hydrogen storage tank placed underneath the backseat

The remaining critical parameter for a broad introduction of fuel cell vehicles are the production costs of fuel cells (currently some 1,000 EUR/kW$_e$). According to the US Department of Energy (DoE) the manufacturing costs of fuel cells can be lowered down to 100 \$/kW$_e$ on the basis of today's state-of-technology. Target costs of 30 \$/kW$_e$ by the year 2015 are stated in the framework of the US FreedomCar programme. DaimlerChrysler, Honda and General Motors/Opel indicate that target costs as low as 50 \$/kW$_e$ for the fuel cell including the electric motor are already achievable on the basis of annual production volumes of 100,000 to 1 million vehicles. Major car companies thus are certain to meet the cost targets required for market penetration.

Meanwhile, various introduction scenarios for hydrogen powered vehicles are discussed world-wide. Some growth projections argue that even in twenty to thirty years fuel cell vehicles will only captures a marginal share of the overall market. Given the number of uncertainties which accompany the introduction of hydrogen powered vehicles, any prognosis can only be vague. An introduction in 'slow motion' is yet very unlikely for one simple reason: Either hydrogen powered vehicles will overcome technical and economic hurdles to be competitive with conventional technology, then the market penetration will proceed rapidly (why should someone not buy the car with the better overall performance). Or hydrogen powered vehicles will not overcome these hurdles and then would finally fail to enter the market at all (why should someone buy the car with the worse performance).

There is a growing number of hydrogen filling-stations both for conventional vehicles which have been converted to use hydrogen as fuel, and for fuel cell-powered vehicles which are now being used on a trial basis in several countries including Japan, Germany (Berlin, Hamburg, Stuttgart) and USA (California, Florida, Washington et al). Some 100 hydrogen refueling stations will be operating world-wide by the end of 2004. Most of them supplying only a couple of hydrogen powered cars or buses per day.

Broad-scale introduction concepts are pursued by Japan and Iceland. In several US states as well as Canada and China, seed demonstration projects are discussed to initiate the built-up of hydrogen infrastructure, mostly along defined corridors (sometimes also subsumed as "hydrogen highways"). The Japanese project is supported by Toyota, Honda and other major corporations to realise a pure "hydrogen economy" on the island of Yakushima. The same applies to Iceland which has abundant renewable energy resources from geothermal sources. The Iceland government announced to subsequently substitute hydrogen for all fossil fuel used nationally. Therefore, a hydrogen refueling station was opened in 2003 in Iceland's capital Reikjavík. Three DaimlerChrysler hydrogen powered fuel cell buses are in regular public transport service (www.ectos.is).

Commercial sales have started of hydrogen-fuelled domestic electricity generation systems, such as the combined heat-and-power systems now being marketed by the Honda Corporation in Japan. Yet, further progress is required in order to penetrate the stationary energy market on a large-scale.

International standards for hydrogen fuel purity, and equipment such as hydrogen fuel tanks for motor vehicles are being pushed forward as a result of negotiations between major Japanese, German and American motor manufacturers, oil companies such as the

Royal Dutch/Shell Group, and others (e.g. EIHP – European Integrated Hydrogen Project, www.eihp.org).

Concerning the public acceptance and social implication of hydrogen and fuel cell technologies, eight studies have been carried out so far most of them in Germany. Three have been conducted in the course of a demonstration project. A first international acceptance study has started in 2003 and will be pursued until mid 2005 [LBST 2004]. Locations included are London (UK), Berlin (Germany), Luxembourg (Luxembourg), Perth (Australia) and Oakland (California, USA). Passengers of hydrogen buses (fuel cells and ICEs) in demonstration projects will be surveyed. By now, two central conclusions may be drawn from the existing studies: Hydrogen acceptance is generally high, and as soon as people experience hydrogen technology in their every-day life they accept and use it.

8.3.3 Further SPS synergies

In this chapter, potential synergies of space-based solar power systems are described which go beyond the scope of this study and its scenarios respectively. The propositions have to be seen in conjunction with space/terrestrial synergies (chapter 8) and technological descriptions in chapter 3.4.

a) Europe power-sharing

Although the major focus of this report is power supply to Europe, the inherently international scope of delivery from satellites in geo-stationary orbit would create potential market opportunities through sharing the output of a European satellite with rectennae outside Europe. Even while focusing on power supply for Europe, it would be a mistake to exclude any consideration of exports and imports from a study of such an inherently global system. That is, drawing conclusions about the system's feasibility while ignoring international exchanges of power would lead to false conclusions - as would the same way of thinking related to terrestrial electricity systems today. Potential microwave power markets include sites both at different longitudes from Europe, and at different latitudes.

Moreover, the subject of the present study is "European Strategy in the Light of Global Sustainable Development" [SOW 2003]. During the 21st century, global electricity demand is expected to grow to 20 times the demand in Europe. If the possibility of Europe developing a space-based solar power supply capability is to be considered as a potential contribution to creating a sustainable global energy supply system, its potential use for supplying non-European countries could be an important part of the value of such a project.

- North-South power sharing

In the time-frame of 2030 and beyond there are likely to be opportunities for extra-Europe power sharing between rectennae in Europe and rectennae in countries south of Europe. These opportunities will increase as demand for electricity in these countries grows, and they are likely to be based on seasonal demand differences rather than time-zone differences. In such a case of seasonal power sharing, a satellite could in principle achieve 97% load-factor while two rectennae each achieved 48.5%. In the case of a rectenna sited in north Africa, the rectenna too could achieve 97% load-factor, while that of the long-distance cable delivering the power to Europe would be nearer 50%. (If power from other base load plants in Europe was delivered to Africa during the summer, the cable too could achieve a high load-factor.) Due to the high insolation in many countries south of Europe, rectennae are likely to be co-sited with terrestrial solar energy facilities there, as discussed further in Section 8.2. A further possibility would be sharing power with rectennae in the southern hemisphere where the winter demand peak coincides with the summer minimum in Europe.

- East-West power sharing

Flexible sharing of the output of a satellite between two (or more) rectennae at different longitudes could be used to profit from the time-difference between electricity demand peaks at sites in different time-zones. One potentially promising case is the delivery of power alternately to rectennae in time zones separated by several hours on the east and west coasts of the Atlantic; in principle a single satellite could serve both morning and evening peak loads in both places. The delivery schedule of a satellite that ceased delivery to one rectenna before starting delivery to the other is shown in Figure 8-21; in this case the rectennae' load-factors would be significantly less than 50%.

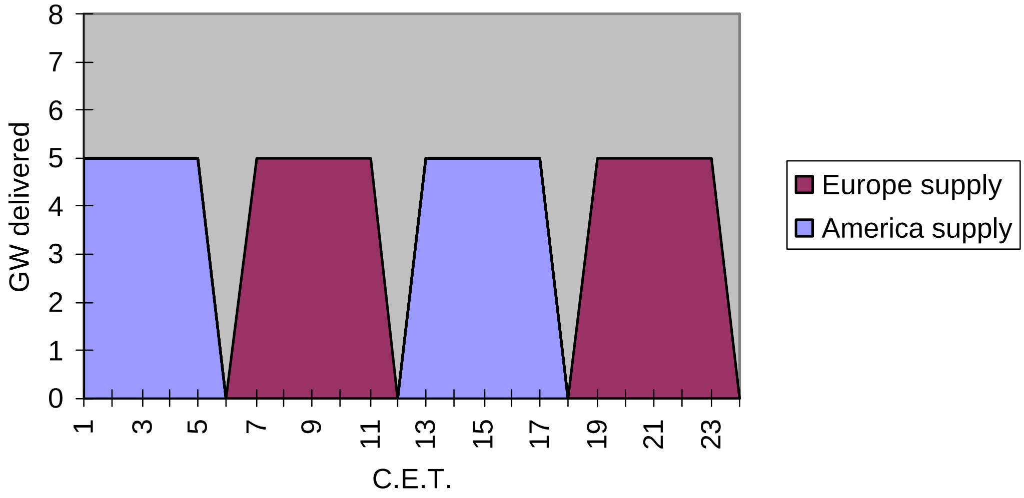


Figure 8-21: Satellite output sharing between trans-atlantic rectennae (1)

Alternatively, designing transmitting antennae with the capability to deliver power simultaneously to two widely separated rectennae would enable a delivery pattern as shown in Figure 8-22. In this case the rectenna load factors could approach 50% and the satellite 97% (the maximum possible due to eclipses).

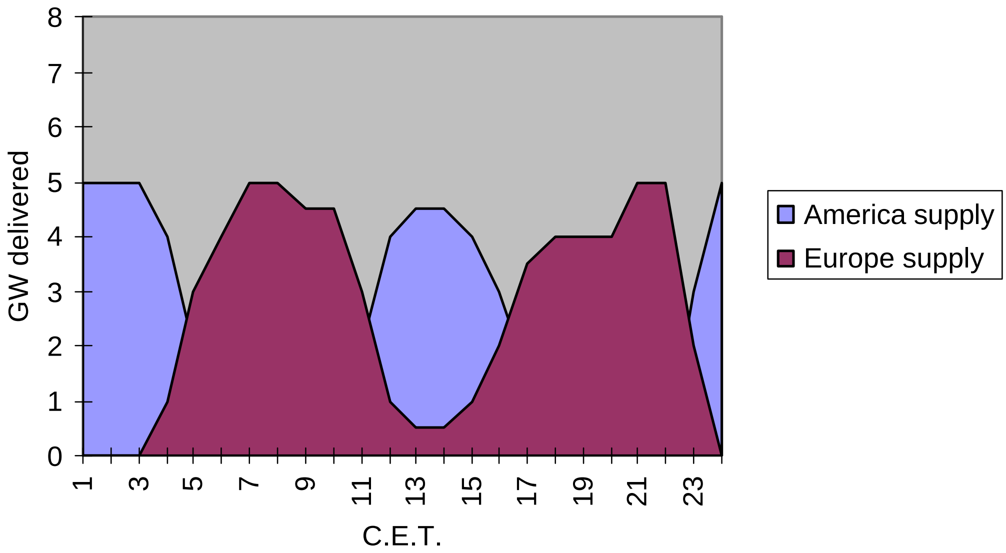


Figure 8-22: Satellite output sharing between trans-atlantic rectennae (2)

Similar opportunities should exist between sites in Europe and sites to the east and south-east of Europe; they will depend on details of local electricity demand patterns for large blocks of power within Europe and in places to the East, including Russia, the Middle

East, India and western China, and more particularly on electricity demand patterns in 2030 and beyond. Claverie & Dupas studied this in 1980, using the criterion that a minimum population density is required in order for electricity demand to be sufficiently concentrated to be supplied by a rectenna [Claverie 1980]. However, they considered demand only until 2025, whereas the major growth of world electricity demand is expected to occur after 2025.

- Competition with long-distance power cables

Modes of operating solar power satellites which involve delivering power to widely separated sites would compete with long-distance terrestrial electric power transmission via cables. For example, the estimates quoted in Section 4.3.3 give the cost of a 10 GW capacity cable from north Africa to central Europe as approximately 3.3 billion Euro [Häusler 1999]; consequently a rectenna in north Africa would cost less than the offshore rectenna in Europe described in Section 3.3.2a). If the cost of long-distance cable transmission fell significantly in future with the development of economical super-conducting cables (whether based on ceramics or on carbon nanotubes) the minimum distance over which switching of space-based microwave power beams could be economically attractive would rise.

Optimistic forecasts for this technology, such as the "GENESIS Project" advocated for more than a decade by Sanyo Corporation [Kuwano, 1990], foresee all national electricity grids being inter-connected with super-conducting cables to permit large-scale shifting of solar-generated electric power around the world on a 24-hour basis. Such a development could even make cable transmission across the Atlantic feasible, and could in principle make east-west switching of microwave beams between Europe and America less attractive. However, it could also open up other opportunities, by reducing the cost of siting rectennae in remote sites where the cost of land was very low.

b) Network synergies

As the numbers of satellites and rectennae increased, opportunities for synergy in their operations would increase, thereby increasing the overall efficiency of their utilisation. These are similar to the synergies seen in computer networks and mobile-telephone networks, of which the value increases with the number of members using the network. In particular, as the number of rectennae increased, the potential value of decoupled operation would increase, as both satellites and rectennae would each have more potential partners.

Some rectenna operators might nevertheless make long-term contracts for delivery of uninterrupted baseload power. However, the additional flexibility that would arise from decoupled operation would make the growth of a wholesale market in microwave power from space likely – in the same way that improved information technology has led to the growth of wholesale markets for terrestrial electricity supplies today.

In addition, it does not seem probable that Europe would develop space-based power alone; it is more likely that European, Asian and American countries would develop the capabilities simultaneously, probably even collaboratively. Consequently the total output capacity of space-based power would be likely to be some three times the capacity being used in Europe. Hence, if European capacity reached 500 GW, worldwide capacity might be some 1,500 GW, and so cost reductions due to scale and learning effects could exceed figures estimated from European capacity alone. This could further increase the potential to operate flexibly at lower rectenna load-factors, and become the basis of the "Planetary Power Web" discussed in the Fresh Look study.

Wholesale market in microwave power from space

Wholesale markets in electric power exist in the USA, Britain and other countries, where they set the current price of standardised contracts for wholesale electric power from different sources, typically on a half-hourly basis. Some key market prices for wholesale electricity are even quoted in daily newspapers. As interconnections between national electricity grids spread geographically, as they have already in Europe in particular, the role of such markets is likely to grow. Subject to important provisos, notably that they are adequately regulated and overseen in order to prevent frauds, exploitation of monopoly power, short-term instability, social injustice and other potential problems, these markets can improve the overall efficiency of utilisation of energy resources. Following the precedent of existing terrestrial wholesale electricity markets, it seems likely that a spot market and/or future market for delivery of microwave power from space to standard specifications would develop as the number of suppliers and users increased. This would add further flexibility to the options discussed above, since supplies would always be available at the current market price.

8.4 Conclusion

Synergies between terrestrial and space-based solar power systems may be expected mainly in the following fields: a) joint operation of terrestrial and space-based solar power systems, b) co-siting of terrestrial solar power plants with rectennae and c) technological synergies from photovoltaic (PV). However, most of these synergies are not on a mutual basis, i.e. terrestrial and space-based solar power systems do benefit at the same time.

From the space-perspective, synergies such as cost reduction and reduction of required area can be expected by jointly operating terrestrial and space-based solar power systems for base and non-base load scenarios, e.g. by substitution of terrestrial energy storage facilities or terrestrial solar power plants which are sited in North Africa (applicable only for the 500 GW scenario with hydrogen storage).

For co-siting, target research would have to assure the technical feasibility and expected positive outcomes from co-siting of rectennae with large-scale photovoltaic systems (with decentralized PV power plants as assumed in the scenarios throughout this report, co-siting is not applicable). Co-siting with solar thermal power plants has to be seen even more critical. Furthermore, it should be noted that co-siting a rectenna is only applicable for large-scale terrestrial solar power plants covering large contiguous areas, typically several kilometers across.

From the terrestrial perspective, mutual space and terrestrial PV synergies can be expected due to the common technology basis (photovoltaic). This may eventually result in a competition between terrestrial and space-based solar power systems as the terrestrial market may profit earlier from these synergies. Due to the longer lead time of the SPS system, the terrestrial power generation market could set off even faster than it may be possible without technological synergies.

9 ENERGY PAYBACK TIMES (WP4)

This chapter consists of several subchapters. In subchapter 9.1 and 9.2 the life cycle energy requirement of different space-based and terrestrial solar power concepts respectively are assessed. In chapter 9.3 conclusions are drawn from the life-cycle analysis. And in chapter 9.4 different built up scenarios and its influence on the actual energy balance and as a result its influence on the maximum allowable growth rate for the addition of new plants has been investigated. Additionally, in chapter 9.5 other energy related issues concerning the life-cycle of terrestrial and space-based solar power plants are discussed.

The life cycle analysis (LCA) assesses the total energy consumed and the total amount e.g. of greenhouse gases (GHG) and air pollutants emitted by a power system over its life cycle. In this study the energy requirement for the electricity generation from different solar power concepts has been investigated. The analysis has been carried out via a process chain analysis whereas the main scope of the study was to assess the total energy requirement and not the associated emissions.

The energy payback time is the time after the plant has generated the amount of energy which is required for the construction of the plants including the manufacturing of its different components and the supply of the materials needed for the construction of the plant.

There are two different definitions for the energy payback time. One approach does not consider the fact that the electricity generated by the renewable energy source replaces electricity from conventional electricity generation such as coal, nuclear, oil and natural gas:

$$Payback\ time = \frac{E_{PE,\,in}}{W_{e,\,out}\,/\,yr}$$

The other definition considers the replaced electricity from conventional electricity generation:

$$Payback\ time = \frac{E_{PE,\ in}}{W_{e,\ out} / yr / \eta_{ref}}$$

where

$E_{PE,\ in}$ Primary energy requirement

$W_{e,\ out}$/yr Annual electricity generation

η_{ref} Electricity generation efficiency of the reference system (e.g. electricity mix)

Generally the second definition has been selected. According to VDI 4661 [VDI 2000] the reference system is included in the calculation of the energy payback time. In this study results for both definitions are presented.

In some literature sources the LCA is carried out using an economic input-output model where the energy use for different activities is calculated on the basis of the costs of goods and services. The economic input-output method often is used in cases when other data are not available. The economic input-output method averages prices across sectors of goods and services and therefore introduces inaccuracies. More important the costs of goods do not necessarily depend on the energy requirement for its production. The costs of goods also are influenced e.g. by currency exchange rates, the level of wages in the different sectors and countries and social contributions. Therefore in this study the LCA has been carried out via a process chain analysis and not via an economic input-output method.

9.1 Space-based solar power systems

9.1.1 History of SPS analysis

To some, it may appear that the discussion of space-based power plants has somewhat neglected associated themes such as that of the energy ratio -- i.e. the comparison of the output of a plant with the investment necessary for its realization – and that the supporters of space power have concentrated in an excessive manner on discussing power availability and economy, an area in which the room for controversy is actually much larger. In truth, space power plants received scrutiny in this respect from very early days – because of the "obvious" argument that transporting such a plant into orbit is "of course" exceedingly energy-intensive.

a) Early NASA studies

Accordingly, already in the mid-1970s it had been disclosed that not only space power stations (SPS) offered a positive energy return, but that it actually would have a very short payback time – of the order of one year [Glaser 1975]. The JSC evaluation [Anon 1976], in comparing a 10-GW SPS with nuclear and coal-fired plants, arrived at following figures:

- primary fuel use (occurring only in the launch year): 3.46 million t
- thermal loss (occurring only in the launch year): 108,000 TJ
- fixed land use: 64 km^2

The same study attempted a first estimate of the payback time (0.83 years) for a 10-GW plant with a mass of almost 0.9 million t (less than 12 W/kg overall). One can derive an energy payback ratio (EPR) of 26 under the assumption that the maintenance investment equals a complete substitution of the rectenna (1.1 million t).

Herendeen and co-workers (1979) [Herendeen 1979] addressed this issue as part of the ground-manufactured NASA/ DoE SPS Reference Concept. Also analyzing a 10-GW plant, those authors assessed an EPR of only 2.1, which – under the assumed maintenance expenditure of 0.8% of the total energy requirement -- corresponds to a 14 to 15-year payback time. The most interesting conclusion that one can draw from that work concerns the distribution of the energy investments among the different subsystems they considered as shown in Table 9-1.

Solar cells	65.7 %
Rectenna:	21.8 %
Space transportation	7.7 %
Ground transportation	3.8 %
Maintenance:	0.8 %
Transmitter:	0.1 %
Space construction	< 0.1 %

Table 9-1: Distribution of energy requirements among the different subsystems

Accordingly, the success of the SPS as a net energy producer depends on the the efficiency of the PV collectors, as further analysis by Spear & Hornberger (1981) [Spear 1981] show. Were the energy investment for the PV arrays halved, the energy payback ratio (EPR) would move up to 3.1. All other elements remain subordinate over a relatively long parametric stretch, including the contribution of the space transportation.

The results of the NASA/ DoE CDEP effort were evaluated in terms of energy payback by Cirillo, Cho, Monarch, & Levine (1980) [Cirillo et al 1980]. Table 9-2 below summarizes the results.

Parameter	Si SPS	GaAlAs SPS
Gross efficiency	7.0%	6.9%
Operating efficiency	7.0%	6.9%
Operating ratio	16.7	77.9
Lifetime efficiency	6.9%	6.9%
Lifetime ratio	3.9	18.0
Payback period	6.4 a	1.3 a

Table 9-2: Net energy indices for the CDEP SPS [Cirillo et al 1980].

Also building on the Concept Development and Evaluation Program (CDEP) Reference Concept, Frantz and Cambel (1981) [Frantz 1981] estimated the energy payback period at 8.5 years for the silicon baseline (with a lower limit of 2.5 years), and at 2.8 years for the GaAlAs version (with a lower value at 2.1 years). Likewise, the net energy ratios were at about 3 (and up to 8) for the silicon, and 7 (possibly up to 10) for GaAlAs variant. To those parameter values correspond a power fraction for operations varying between 3.2% and 7.0%.

b) Lunar power system

One of the best-documented recent system concept for space power plants is the Lunar Power System, studied since mid-1980s by David R Criswell and his collaborators. In particular, Criswell (1991) [Criswell 1991] offered a comparison of a range of different power-generation approaches, showing the clear superiority of the space systems in terms of energy ratio. He quoted a four-month energy payback time at the rectenna's end, although apparently at least some energy expenditures on the Moon (metal refining, transportation from the Moon surface into lunar orbit, etc) are included in the analysis.

c) Other early work

The concept of net return on the energy investment is also of basic importance in the discussion of the impact of satellite power stations by Yamagiwa & Nagatomo (1992) [Yamagiwa 1992]. As a number of authors before them (see e.g. [Bernasconi & Woods, 1993], [Bernasconi 1997] for a short review), they used the cornerstone of the environmentalist politics – Forrester's WORLD model – to search for alternative approaches that might avoid killing off several billion people during the twenty-first century (Figure 9-1). In their first assessment, Yamagiwa & Nagatomo (1992) set out by discussing the energy investments necessary to establish an SPS system, taking a look at the satellite's hardware, the propellants' requirements and associated expenditures, and the launch vehicles themselves. In addition to considering the CDEP Reference Concept, they assumed expendable launch vehicles delivering all the necessary mass from the Earth surface to GEO, thus making their analysis robustly conservative.

Using an appropriate modification of the WORLD-2 model to assess the flow of energy-related, terrestrial natural resources (oil, coal, & natural gas) and to include an SPS section, Yamagiwa & Nagatomo (1992) finally looked at the consequences of investing different fractions of the yearly energy usage rate to support realization of an SPS system. As long as the investment remained below 0.5%, the model predicted continuing pollution increase and population decline; at higher investment levels, population was sustained and there appear a begin in recovery of the quality of life, "because the rapid growth of SPS... can support the growth of energy consumption... the growth of SPS can be supported by the energy returned to the Earth by SPS itself. Once this condition is reached, the limits to growth on Earth can be completely removed [over a horizon of several centuries]"(Figure 9-2)

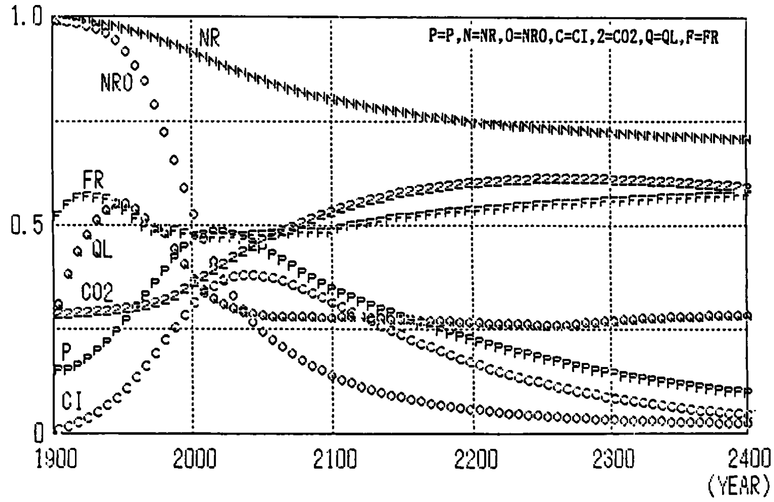


Figure 9-1: The future according to WORLD, recomputed with the updated version used by Yamagiwa; note that the population's full scale value corresponds to 10 billion (from Yamagiwa & Nagatomo, 1992).

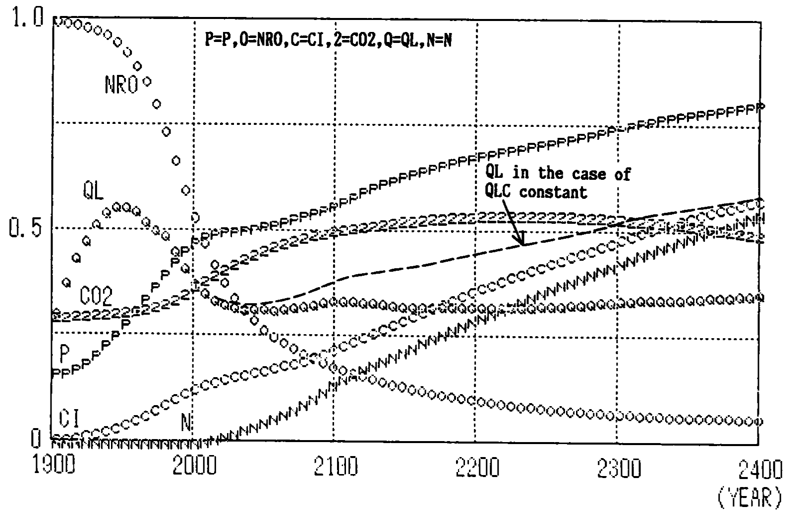


Figure 9-2: Results of the world dynamics simulation with SPS, with an investment of 1% of the energy usage (from Yamagiwa & Nagatomo, 1992)

While the actual predictive power of the WORLD series of models remains widely open to question, the fundamental issue addressed by the Japanese researchers, and by their colleagues who performed similar studies, was to show how the model could indeed respond to the inclusion of a better reality approximation with quite different results. But in addition, Yamagiwa and his colleagues focused primarily on the energy investment aspects, and were able to show that – even starting from conservative assumptions, like expandable launchers, Earth manufacture of SPS, etc – the space option yielded significant improvements.

Weingartner & Blumenberg (1993) [Weingartner 1993] critically revisited the Reference Concept to examine afresh its potential for energy payback, extending their considerations to different flavors of PV plants and to a solar-dynamic option (Figure 9-3). They also mention LEO-based systems, concluding that such plants need payback times longer by an order of magnitude, and therefore suggesting that LEO systems may only be of relevance for demonstration missions. Finally, Weingartner & Blumenberg (1993) review the potential of lunar resources' usage, correctly pointing out that this introduces "a big difference concerning the Earth's energy balance... In the case of lunar cell production, the energy is invested on the Moon, provided by lunar-based power systems, and consequently the net energy flow to the Earth is increased."

They concluded by comparing the payback times of solar and terrestrial power plants. In this "head-on" comparison between ground and space plants, they came to the surprising (for them) conclusions of the superior potential of the space option (Figure 9-4).

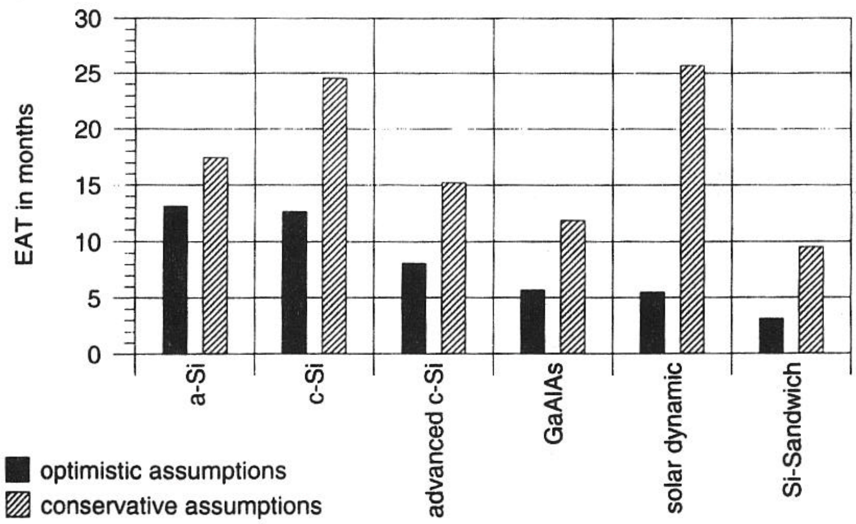


Figure 9-3: Payback time (EAT) for GEO power plants (from Weingartner & Blumenberg, 1993).

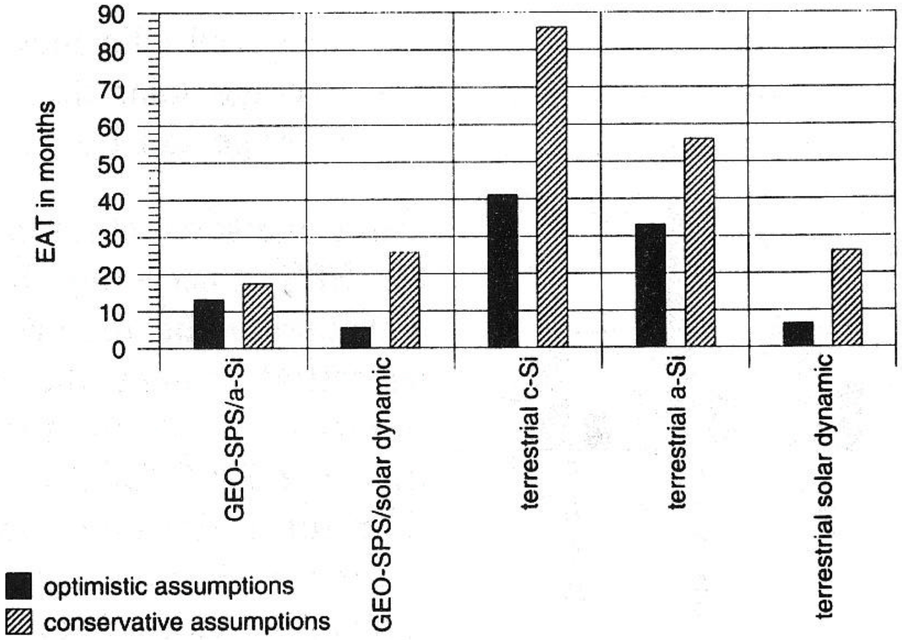


Figure 9-4: Comparison of payback time (EAT) for space-based and terrestrial power plants (from Weingartner & Blumenberg, 1993)

9.1.2 Space option plants

a) Power plants summary

Table 9-3 summarizes the major parameters of the space plants referred to in this Study. The production capacity for the geostationary plants is assumed to be limited only by the eclipse season. For the medium-altitude earth orbit (MEO) constellation, it was assumed that eight plants would supply twice the single rated power level, continuously. The materials inventory for the different plants is taken from the original reference, complemented by some engineering assessments.

Nominal power level	250 MW	1 GW	5 GW	10 GW
Fuel	na	na	na	na
Capacity factor	25%	99.3%	99.3%	99%
Lifetime	30 a	30 a	30 a	30 a
Remarks	Sun Tower, in MEO constellation	Solar Disk in GEO	Solar Disk in GEO	Solar Disk in GEO
	No energy storage	Complemented by energy storage	Complemented by energy storage	Complemented by energy storage

Table 9-3: Power plants used in the different scenarios (0.5 GW, 5 GW, 150 GW, 500 GW)

Here, we characterize the four power stations used in the previous scenarios mainly through their masses (Table 9-4). The "Fresh Look" report allows but a limited detail in the formulation of the mass breakdown. We have cross-checked the amount of attitude an orbit control system (AOCS) propellant, using the characteristics and requirements indicated by Feingold and colleagues [NASA 1997]; their report also includes the specific figure for the 5-GW plant. A noteworthy point concerns the propellant load that – for the geosynchronous earth orbit (GEO) plants suffices for the first 30 years of operation, assumed as lifetime in the present Study. Lacking similar data for the medium-altitude earth orbit (MEO) plant, we can only assume that their propellant load will be replenished at least once during their useful lifetime, and the figures in Table 9-4 reflect this assumption. Also, we attempted to model a split of the "platform" mass between structure and other items (Command & Data Handling (C&DH), etc – i.e. mostly electronic components).

Unfortunately, the "Fresh Look" report does not include assumption about the rectenna mass. Herendeen and co-workers (1979) [Herendeen 1979] ran up a rectenna mass estimate of 6.36 million t, for an assumed surface of 45 km^2: this obviously correspond to 141,333 t/km^2, or 141 kg/m^2. As this would suffice to cover the surface with 16-mm thick steel plates or (more accurately reflecting their assumptions) 30 mm of concrete covered with 8 mm of steel, we re-examined the area-specific figures, and assessed the mass of the panel structure shown in [Hanley 1980] at some 20 kg per square meter of rectenna land surface.

Plant Type		250 MW	1 GW	5 GW	10 GW	Assumption
Unit Mass Breakdown - Space						
Power transmission	t	1384	8387	41858	83716	Electronics
Solar collection	t	1592	2314	11544	23088	Silicon
AOCS	t	30	63	578	1573	Chromium
Structure	t	355	728	6690	15279	Aluminum
C&DH, misc	t	40	40	100	150	Electronics
AOCS propellant	t	300	670	3683	9200	Argon
Pro-rata launch vehicle	t	166	530	1945	3872	Titanium
Pro-rata propellant	t	55856	173775	914388	1886799	LOX+LH2 6:1
Mass of a space segment unit	t	3701	12202	64453	133006	--
Unit Mass Breakdown - Ground						
Rectenna surface area (average)	km^2	2.93	9.86	49.31	50.44	
Structural elements	t	2051	6902	34517	35308	Aluminum
	t	46880	157760	788960	807040	Concrete
	t	5860	19720	98620	100880	Steel
Electronic parts	t	3809	12818	64103	65572	Electronic parts
Mass of a ground segment unit	t	58603	197210	986249	1008850	

Table 9-4: Mass breakdown of the space and ground segments of the various plants

The number of launches was obtained from the consideration of the mass to be orbited, while the number of vehicles derived from the assumption that each could perform 12 flight per year; in addition, fleet attrition (through vehicle loss and retirement of high-time items) was modeled along the lines of the original discussion by Koelle (1997) [Koelle 997]. Finally, the vehicle mass to be procured (Table 9-5), and the propellant mass used in operations was pro-rated with the number of plants in the respective scenario.

Plant Type	250 MW	1 GW	5 GW	10 GW
Cumulative missions number for the scenario	90	175	5525	19001
Deployment time scenario	2	5	15	25
Vehicles produced scenario	4	4	42	92
Pro-rated vehicle mass	332 t	530 t	928 t	1220 t
Pro-rata propellant mass	55856 t	173775 t	914388 t	1886799 t

Table 9-5: Summary of earth to low earth orbit (ETLO) transportation parameters for the different scenarios

Finally, one needs to assess the energy requirements for space transportation: we used the 6000-t Neptune heavy lift earth launch vehicle (HLLV), a conservative (three-stage) reusable ballistic system capable of delivering 100 t to lunar orbit [Koelle 1997]. In the present analysis, Neptune carries its net indicated payload of 350 t to LEO. The Neptune launcher has an overall dry mass of 663 t, and carries a 4965-t propellant load.

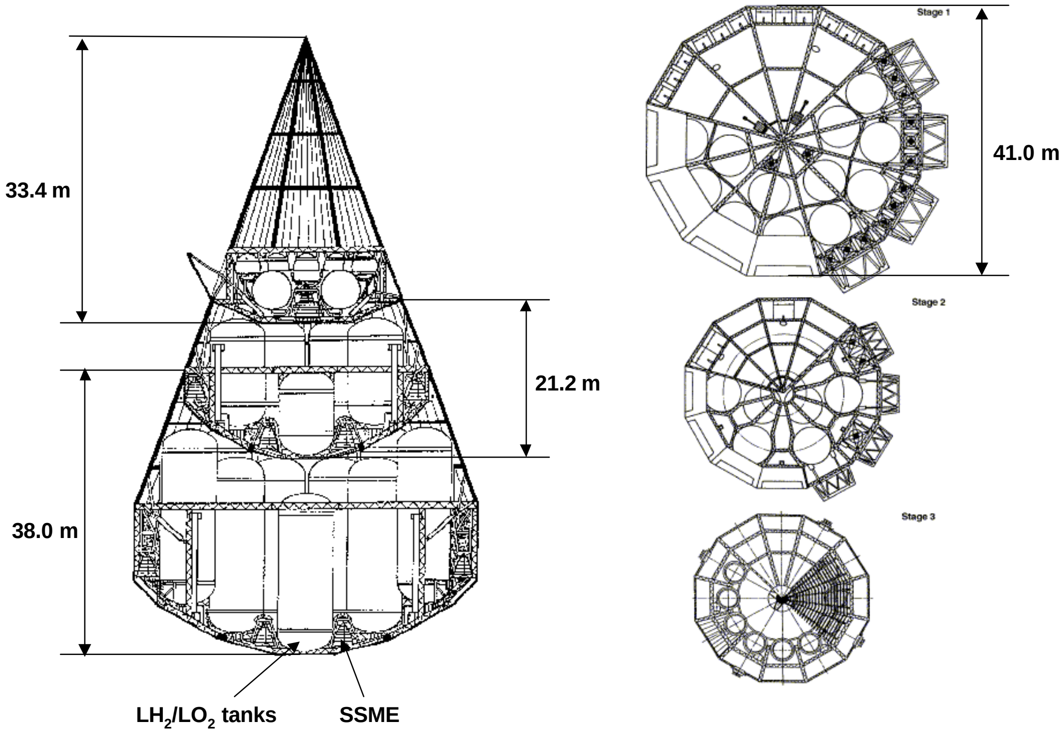


Figure 9-5: Neptune heavy lift earth launch vehicle (HLLV) [Koelle 2002]

The first stage employs 40 space shuttle main engines (SSME), the second stage employs 9 SSME, the third stage employs either 1 SSME or up to 12 of smaller engines [Koelle 2002].

b) Plant installation investments

- Materials-embodied energy

To begin the assessment of the energy investment necessary for the production of the plants, the specific energy intensities for the materials used are necessary. Table 9-6 summarizes such data, as used in previous work paralleling the aims of the present Study, and illustrates the order of magnitude and the range of the materials energy intensities.

Material	Energy Requirement [GJ/t]	Reference
Primary aluminum	173	(GEMIS, 2002)
Argon	32	(Herendeen & al, 1979)

Material	Energy Requirement [GJ/t]	Reference
Chromium	116	(GABIE, 2002)
Concrete	1	(GEMIS, 2002)
Primary copper	53	(GEMIS, 2002)
Electronic parts	250	(Herendeen & al, 1979)
Fiberglass	31 - 34	(GEMIS, 2002; Stiller 1999)
Helium	536	
Liquid hydrogen	492	(GHW 2001; Air Liquide 2002)
Iron	24	(Meier, 2002)
Primary lead	27	(GEMIS, 2002)
Molybdenum	378	(Meier, 2002)
Liquid oxygen	6	(GEMIS, 2002)
Plastics	54	(Meier, 2002)
Metallurgical silicon	141	(GEMIS, 2002), (KfA, 1992)
Silver	16800	
Steel	20	(GEMIS, 2002)
Stainless steel	56	(GEMIS, 2002), (ESU, 1996), (GABIE 2002)
Titanium	920	(Smil, 1999)
Vanadium	3711	(Meier, 2002)

Table 9-6: Materials energy intensity

Following the lead by White & Kulcinski (1998) [White 1998], we computed the embodied energy in the transportation vehicles based on the energy intensity of titanium: this ought to result in a very conservative estimate. Further, one should note that the propellant mixture ratio amounts to 6:1 (liquid oxygen to liquid hydrogen), as the Neptune configuration used here incorporates Space Shuttle main engines (SSME) engines in the first two stages.

The number of plants installed per year followed the assumptions quoted in the "Fresh Look" Study (i.e. up to four Sun Towers, and to two Solar Disks).

The updated mass breakdowns for the space and ground segment's units in the different scenarios are given in Table 9-4, where we have also indicated the materials assumed to represent the energy intensity of the various components. Clearly, even with the relatively light rectenna panel, those elements' mass predominate, being actually comparable to the mass of the propellants needed for orbiting the SPS items.

Using the energy intensities listed in Table 9-6, we then obtain the estimates for the energy embodied in the materials shown in Table 9-7. The space transportation propellants do indeed constitute the largest fraction of the materials energy requirements, followed by the wireless power transmission (WPT) components. Notice that a significance difference in the relative mass of the power transmission appears between the Concept Development and Evaluation Program (CDEP) and the Fresh Look Study. The latter does not give enough detail to explain it fully, especially as the working frequency moved up to 5.8 GHz; it may be related to a higher power density over the aperture (and the associated waste-heat rejection issues), to lower mass efficiency of the automatic orbit installation, or to some other factor. In any case, as the spaceborne transmit antenna dominates the space plant's mass, it appears as a logical focus for further development work.

		Space Segment			
Power transmission	TJ	346	2097	10465	20929
Solar collection	TJ	224	326	1628	3255
AOCS	TJ	3	7	67	182
Structure	TJ	50	103	950	2170
C&DH, misc	TJ	10	10	25	38
AOCS propellant	TJ	10	21	118	294
Pro-rata launch vehicle	TJ	152	488	1789	3562
Pro-rata LOX	TJ	239	745	3919	8086
Pro-rata LH2	TJ	3926	12214	64268	132615
Energy per unit	**TJ**	**4962**	**16012**	**83228**	**171132**
		Ground Segment			
Aluminum	TJ	291	980	4901	5014
Concrete	TJ	47	158	789	807
Steel	TJ	117	394	1972	2018
Electronic parts	TJ	952	3205	16026	16393
Energy per unit	**TJ**	**1408**	**4737**	**23689**	**48463**
Total materials energy E_mat	**TJ**	**6369**	**20749**	**106917**	**219595**

Table 9-7: Energy embodied in the SPS plants' materials

- Solar array manufacture

In order to calculate the energy requirements for the PV array the data for the Uni-Solar UPM-880 module, neglecting both the aluminum frame and the steel backplate has been used. The resulting blanket, however still builds on a 5-mil (0.127 mm) thick steel foil and includes an encapsulation of Tefzel[13]/EVA[14] most probably of 6 mil (0.152 mm).[15] In economic terms, such elements would not represent an optimum for use within a space system. In energy terms (Table 9-8), the encapsulation is by far the most significant component, actually followed by the conductive oxide layer; the massive (> 1 kg/m^2) substrate contributes only about a tenth of the overall embodied energy. The last two

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[13] Tefzel is a trademark of DuPont and consists of a modified copolymer of tetrafluoroethylene and ethylene

[14] Ethylene vinyl acetate

15 Reference is made here to the thinner blankets produced by Iowa Solar, using a 2-mil polymer backing, and for which an overall thickness of 8 mils is quoted. Note that UPM-880 no longer appears in the current Uni-Solar catalog.

columns in Table 9-8 document a first linear attempt at scaling those data in the direction of a blanket for space use: an additional inorganic layer is assumed for the encapsulation, the substrate is represented by a one-third of the previous encapsulation values, the other numbers are left unchanged. By consequence, the energy value drops by one-third.

Future technology improvements are subsumed by applying a higher PV module efficiency. The efficiency of the Uni-Solar UPM-880 module is indicated with 5.7% [Meier 2002] whereas the efficiency of the PV modules assumed for the space system is a assumed to be 9.2% as indicated in [NASA 1997]. It is possible that the higher efficiency is achieved by adding more layers which leads to a higher energy requirement for the manufacturing process. Therefore the reduction of required energy for the production of space addatped PV modules as done above might be an optimistic approach and might lead to an underestimate of the required energy for the production.

Item	**Material**		**Fabrication**		**Scaled -- Material**	**Scaled -- Fabrication**
	[MJ/module]	[MJ/m²]	[MJ/module]	[MJ/m·]	[MJ/m·]	[MJ/m·]
Encapsulation	90	210	56	137		75
Substrate	10	26	23	56	70	46
PV layer			38	92		92
TCO	7	19	40	97	20	97
Back reflector			30	74		74
Passivation & gridding			14	33		33
Total		**255**		**489**	**90**	**417**
				744		**507**

Table 9-8: Energy embodied in UPM-880 (approximated, after Keoleian, 2003) & scaled towards a space blanket

The results from the considerations summarized in Table 9-8, combined with the parameters from the Solar Disk description, yield the manufacture estimate shown in Table 9-9.

Plant Type		**250 MW**	**1 GW**	**5 GW**	**10 GW**
Solar array extension	m²	2844000	11376000	56900000	113760000
Materials consideration	kg/m²	0.2	0.2	0.2	0.2

	MJ/m^2	28.6	28.6	28.6	28.6
Nominal materials & fabrication (Table 9-8)	MJ/m^2	507	507	507	507
Energy intensity increment	MJ/m^2	478	478	478	478
Solar array embodied energy	TJ	1361	5442	27210	54420

Table 9-9: Estimate of the energy for the space solar arrays

The energy requirement including the energy intensity of the used materials is 507 MJ per m^2. Subtraction of the energy intensity of the materials (28.6 MJ/m^2) leads to about 478 MJ/m^2 which is needed for the manufacturing process alone. The 28.6 MJ/m^2 are derived by multiplying the 0.2 kg/m^2 with the energy intensity of metallurgical silicon.

- Launch facilities

Analog to the calculation of the energy requirements for the manufacture of the plants, a calculation of energy requirements for the erection of the launch facilities has been carried out. The assessment of the necessary plant's investments has been done by referring to the Saturn VAB and crawler data, scaling them up to the Neptune masses. The VAB was conceived to processes up to four Saturn V launchers: here, the assumption was taken that only two Neptune vehicles be handled in parallel, with a throughput of 50 launchers per year. Under Koelle's (1997) assumptions, a launch position has a capacity of 25 cycles per year: accordingly, each assembly building serves two launch positions. Of course, the number of necessary launch positions follows from the cumulative number of launches, the plant's system deployment time, and from the position's launch rate capability.

Plant Type		**250 MW**	**1 GW**	**5 GW**	**10 GW**
Assembly buildings		1	1	8	16
Concrete	t	187'190	187'190	1'497'521	2'995'042
Steel	t	101'672	101'672	813'376	1'626'752
Concrete	TJ	187	187	1'498	2'995
Steel	TJ	2'033	2'033	16'268	32'535
Subtotal buildings	TJ	2'221	2'221	17'765	35'530
Launch positions		2	2	15	31
Concrete	t	509'628	509'628	3'822'206	7'899'227
Steel	t	29'024	29'024	217'683	449'878
Stainless steel	t	254	254	1'904	3'934
Concrete	TJ	510	510	3'822	7'899
Steel	TJ	580	580	4'354	8'998
Stainless steel	TJ	14	14	107	220

Plant Type		250 MW	1 GW	5 GW	10 GW
Crawler energy	TJ	13	25	776	2'669
Subtotal positions	TJ	1'117	1'129	9'058	19'786
Total launch facilities	TJ	3338	3350	26823	55316

Table 9-10: Launch facilities assumptions and required energy

- Space infrastructure

The concepts discussed in the "Fresh Look" study rely on robotic assembly and relatively large transfer vehicles for the erection of the space plants. Accordingly, we used the yearly productivity of the robot as given by Feingold and colleagues in the "Fresh Look" study [NASA 1997] to assess the size of the robot fleet (Table 9-11)

Similarly, from the payload capacity of the assumed transfer vehicles, we derived the number of flights and followed to the fleet size through the proportionality factor showing up in the "Fresh Look" data. Because of the lower Δv requirement for the MEO orbits of the 250 MW plants, we reduced that fleet size by half (against the assumptions for the LEO to GEO case). Further the propellant consumption has been reduced for the 250 MW plants.

Finally, the embodied energy for the space infrastructure results from the fleets and mass models, using the materials assumptions and data put derived from "Fresh Look" study [NASA 1997] (Table 9-11).

Plant Type		250 MW	1 GW	5 GW	10 GW
Assembly robot mass	t	0.5	0.5	0.5	0.5
Annual robot productivity	t	2365.2	2365.2	2365.2	2365.2
Size of required robots fleet	t	7	6	55	113
Transfer vehicle dry mass	t	128	128	128	128
Transfer vehicle payload	t	437	437	437	437
Transfer vehicle propellant load	t	59	118	118	118
No of transfer vehicle's flight per year		36	28	295	608
Required number of transfer vehicles		7	11	121	250
Robots mass	t	4	3	28	57
Transfer vehicles mass	t	940	1'467	15'498	31'981
Argon Propellant	t	4'225	16'478	522'246	1'796'188
Liquid hydrogen	t	10'475	36'373	1'089'809	3'704'954
Liquid oxygen	t	62'849	218'236	6'538'854	22'229'726

Plant Type		250 MW	1 GW	5 GW	10 GW
Embodied energy:					
Aluminum	TJ	134	209	2'205	4'549
Argon	TJ	135	527	16'712	57'478
Liquid hydrogen	TJ	5'154	17'895	536'186	1'822'838
Liquid oxygen	TJ	314	1'091	32'694	111'149
Total	TJ	5'737	19'723	587'797	1'996'014

Table 9-11: Space infrastructure models and energy requirements

- Construction energy estimate

By combining the results shown in Table 9-9, Table 9-10, and Table 9-11, one arrives at the total construction energy values for the different systems shown in Table 9-12, as well as to the pro-rata investment for each plant.

Plant Type		250 MW	1 GW	5 GW	10 GW
Launch infrastructure	TJ	3338	3350	26823	55316
Space infrastructure	TJ	5737	19723	587797	1996014
Space segment	TJ	10884	27210	816303	2721008
Total	TJ	19959	50282	1430923	4772338
No of plants in relevant scenario		8	5	30	50
Construction energy per unit	**TJ**	**2495**	**10056**	**47697**	**95447**

Table 9-12: Construction energy

9.1.3 Operations, maintenance & decommissioning

As defined in the upstream references, the installed GEO space segment already carries a propellant complement to last for its life prior to refurbishment, set a 30 years in the nominal ("most likely") case. Accordingly, the operations expenditures seem limited to remote monitoring and control of the spacecraft from a ground operation center. Operation expenditures at launch facilities are already considered (e.g. diesel consumption for crawler propulsion).

In case of terrestrial plants the decommission energy expenditure can be neglected. In case of space systems the energy requirements for decommissioning can be significant. On the other hand realization of any SPS system with a sensible output (i.e. probably already beginning with the 5-GW European scenario) would result in the opening of geolunar space as a new economic arena. Thus, thirty years later, one can expect that the plants would find use, as extended-life systems after refurbishment, as source of scavenged parts or materials, or as input for bulk recycling. Consequently in this study no energy requirements for decommissining has been considered.

9.1.4 Payback ratios & times

The results of the above analysis are collected in Table 9-13 and compared with the energy obtained from the different types of plant, to arrive at estimates for the energy payback ratio and for the payback time.

Plant Type		**250 MW**	**1 GW**	**5 GW**	**10 GW**
Total materials energy E_mat	TJ	6369	20749	106917	219595
Construction energy per unit	TJ	2495	10056	47697	95447
Total energy investment E_inv	**TJ**	**8864**	**30805**	**154614**	**315042**
		Energies			
Net output power	GW	0.06	0.99	4.97	9.9
Energy output per year	TJ/a	1971	31315	156576	312206
Net lifetime energy output	TJ	59130	939457	4697287	9366192
Energy payback ratio		**6.7**	**30.5**	**30.4**	**29.7**
Payback period	**a**	**4.5**	**1.0**	**1.0**	**1.0**

Table 9-13: Net-energy analysis summary

All concepts appear viable, in that they give a net energy output, with a payback time shorter that the expected lifetime. Because of its low utilization, the MEO plant approach appears rather marginal, however.

9.1.5 Conclusions SPS

The energy payback period -- of the order of one year (or 12 months) for the GEO plants – seems reasonably short. It is essentially balanced with the assumed installation rate of the 1-GW plants (one per year); the higher-power scenarios (150 and 500 GW) require a faster investment, with two plants installed per year, and seem to exemplify the major issue of supplying power in the century, to wit how to cover large needs growing in short times.

9.1.6 Non-base load scenario: LCA of PV plants

For space-based solar power plants no non-base load scenarios has been considered because space-based solar power plants are more suitable for base load operation.

9.2 Terrestrial solar power systems

9.2.1 Approach and methodology

The primary energy effort is calculated along all stages of product life ('from cradle to grave'). For the terrestrial part, this task is done by applying the LBST proprietary software E3 database.

The E3 database is a tool for the calculation of energy and material flows (input, output, emissions) and costs. The E3 database is based on a standard SQL database and contains proprietary analysis and visualization tools The E3 database considers

- Energy and material consumption
- Greenhouse gas emissions (GHG) such as CO_2, CH_4, N_2O, CF_4, SF_6 and HFC
- Air pollutant emissions such as SO_2, NO_x, NMVOC, CO, dust and particulate matter
- Costs

In chapter Fehler! Verweisquelle konnte nicht gefunden werden., a brief overview over preceding studies in the field is given. Reference energy systems are defined for today and 2030 (chapter 9.2.3). The primary energy effort for the two major scenarios (WP1 and WP2) are then calculated. At first, for each scenario the basic functional units – such as steel production, wafer production or PV assembly – are defined (chapter 9.2.4). The data comprise the relevant input output flows of material and energy. These functional units are then interconnected to form a so-called 'chain' according to the scenario type and the technology applied therein. Finally, the primary energy effort, the resulting emissions and their environmental impacts are iterative calculated for each scenario (base load chapter 9.2.5, non-base load chapter 9.2.6).

Regarding data extrapolation for 2030, we decided to follow a conservative approach by applying medium to less optimistic assumptions concerning technology development. E.g. silicon solar cells were taken into account for terrestrial solar power systems. In case major break-through is made in the field of industrial-scale thin film production at an appropriate cost and quality – result data would gain.

9.2.2 History and sensitivity of results

Meanwhile, a great number of studies exist which assess the energy effort for manufacturing, operation and decommissioning of power generation systems. What can be observed is, that results of energy effort assessment are significantly sensitive towards the assumptions made in terms of the selected technology type (see Figure 9-9 on page 9-322), system design and frame conditions. Thus, results without indicating major assumptions lack comparability for reasons of lack of transparency. Even when looking at results which come prior to energy payback calculation (i.e. intermediate results on a less aggregated level), this problem is only marginally eased.

Source	**Energy effort kWh_{PE}/kW_{peak}**
[Hagedorn 1992]*	17,540
[Knapp 2000]	18,901
[Alsema 2000]	13,968
[Jungbluth 2001]	14,889

* without frame and DC/AC converter

Table 9-14: Comparison of study results from energy effort assessments for PV systems (see also Figure 9-9 in chapter 9.2.6f))

In order to calculate the energy payback time, results from Table 9-14 have to be divided by the annual solar power production per kW_{peak}. The annual solar power production varies depending on the local irradiation values. For example, when considering the band width of solar irradiation, even within the 'EU sunbelt' (Portugal, Spain, Italy, Greece and Turkey) one finds the following range of results depending on the worst-case and best-case pairs of energy effort and solar irradiation values (Figure 9-15). If further calculation the energy payback time according to DIN, the preceding energy payback time has to be multiplied by the electricity mix which applies to the time.

		Worst-case parameter pair	**Best-case parameter pair**
Energy effort	kWh_{PE}/kW_{peak}	18,901 [Knapp 2000]	13,968 [Alsema]
Location	–	Ankara (Turkey)	Badajoz (Spain)
Power generation	kWh_e/yr	1,198 * [PV-GIS 2004]	1,463 * [PV-GIS 2004]
Energy payback time	**a**	**15.8**	**9.5**
Efficiency electricity mix	%	35.7	35.7
Energy payback time **	**a**	**5.6**	**3.4**

* optimum orientation, system performance ratio PR = 0.75
** according to DIN (the electricity generation efficiency of the reference system is considered)

Table 9-15: Example of result sensitivity in energy payback calculation of power generation systems (here: PV)

Until the beginning of the 1990ies, PV systems were manufactured on a laboratory scale. The equipment was not optimized towards low energy consumption. Studies carried out since 1990 show that terrestrial photovoltaic plants yield a valid EPR even with the manufacturing technology of the late 1980ies. Later studies proved a constant reduction of energy intensity for PV production as substantial progress was made during the 1990ies. Especially renewable energy technologies dynamically progressed after entering industrial production (wind, PV).

For this study, data basis thus has to be as much up-to-date as possible, including a calculation process which is transparent concerning its selected main parameters.

9.2.3 EU electricity mix

For the supply of construction material for the construction of solar thermal plants, photovoltaic plants, electrolyzers and other equipment assumptions for the used electricity mix has been made. Table 9-16 shows the requirement of primary energy for electricity generation from the power plant mix of the EU-15 in 1999.

	Input [kWh_{PE}/kWh_e]	Output [kWh_e]
Biomass	0.007	-
Brown coal	0.197	-
Hard coal	0.557	-
Geothermal	0.002	-
Hydro power	0.124	-
Oil	0.244	-
Natural gas	0.345	-
Nuclear	1.136	-
Waste	0.185	-
Wind power	0.004	-
Electricity	-	1.000

Table 9-16: Power plant mix EU-15 in 1999 [GEMIS 2002]

The total primary input for the generation of one kWh of electricity from the EU power plant mix in 1999 was about 2.8 kWh. As a result the average efficiency of the EU power plant mix in 1999 was some 35.7%. The share of renewable electricity of the EU-15 electricity mix in 1999 was approximately 14%. The share of renewable electricity of the EU-30 electricity mix in 2020 has been assumed to be some 26% which can be considered as a conservative assumption. The power plant mix has been created using the predictions for 2020 described in [Eurelectric 2001] combined with the EU targets and national targets in different EU countries. According to the EU Directive 2001/77/EC [EU 2001] the share of renewable electricity within the EU-25 has to reach at least 21% until 2010.

Table 9-17 show the primary energy requirement for the generation of electricity from the European power plant mix in 2020.

	Input [kWh_{PE}/kWh_e]	Output [kWh_e]
Biomass	0.075	-
Brown coal	0.216	-
Hard coal	0.247	-
Geothermal	0.005	-
Hydro power	0.153	-
Oil	0.095	-
Natural gas	0.667	-
Nuclear	0.597	-
Biogas (fermentation)	0.008	-
Solar power	0.002	
Waste	0.087	
Wind power	0.080	-
Electricity	-	1.000

Table 9-17: Power plant mix EU-30 in 2020

Then the total primary input for the generation of one kWh of electricity from the EU power plant mix in 2020 would be about 2.23 kWh and the average electricity generation efficiency would be 44.8%.

9.2.4 Basic materials

The definition of basic materials concerning their specific primary energy effort is stated in the Report Annex (see chapter A5).

9.2.5 Base load scenario: Life-cycle analysis of SOT power plants

For the base load scenarios in WP1 solar thermal (SOT) plants with central receiver has been selected. The solar thermal power station has a thermal storage which leads to an equivalent full load period of some 6,400 hours per year as described in [S&L 2003]. The maximum electricity output of the solar thermal plant is 220 MW. For base load scenarios the plant has to achieve more than 8,400 full load hours per year. Therefore an additional electricity storage based on hydrogen has been added. The implementation of the hydrogen storage lead to an electricity output of some 108 MW and an equivalent full load period of 8,400 hours per year (Figure 9-6).

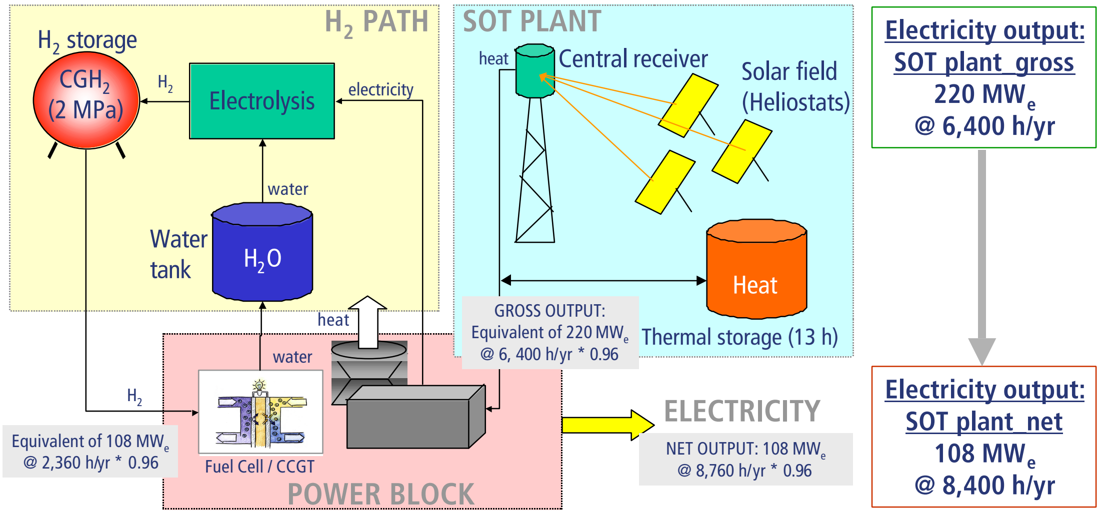

Figure 9-6: Layout of the solar thermal power station with additional electricity storage via H_2

Figure 9-7 shows the process chain analysis of the solar thermal power plant with hydrogen storage.

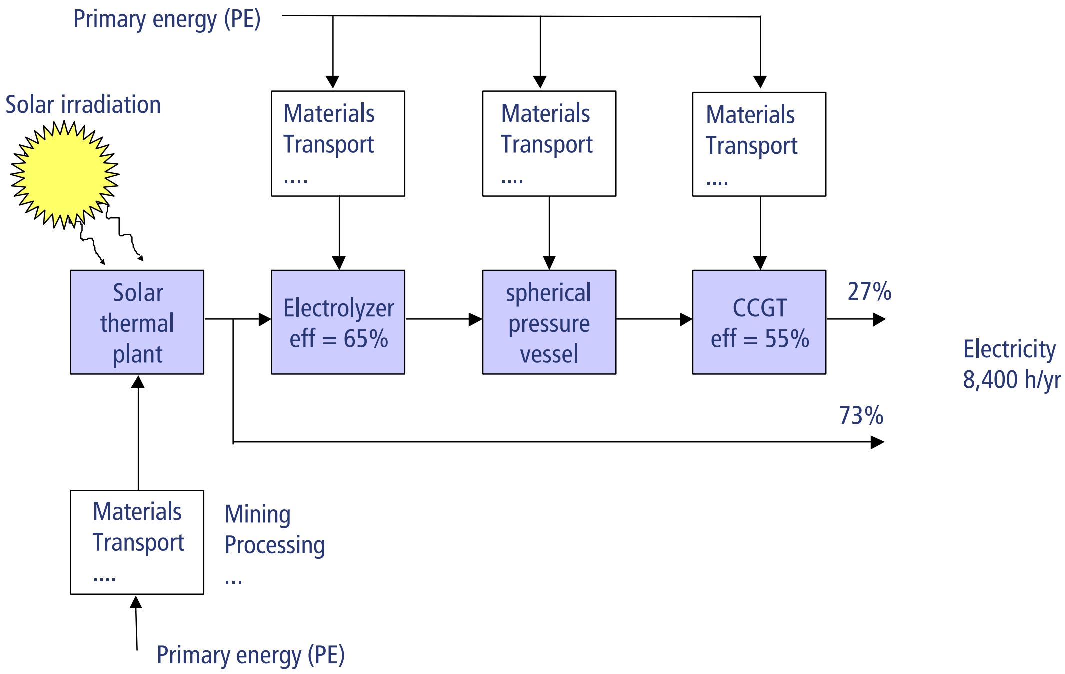

Figure 9-7: Process chain analysis solar thermal plant with H_2 storage

a) Solar thermal power plants with central receiver

In [Romero 2000] the design of a solar thermal power plant with central receiver and with a capacity of 10 MW_e has been described which will be built in Spain. The demand of construction material for the heliostats, the tower and the thermal storage of the 10 MW_e plant has been scaled to the 220 MW_e plant used in this study (108 MW_e fed into grid for the case when H_2 storage is considered). The requirement of construction material for the power block has been derived from a conventional power station.

The material composition of the heliostats has been derived from a 10 MW solar power plant described in [Romero 2000]. The thickness of the glass made mirrors for the heliostats is 3 mm. The support structure is made of steel. The foundation is made from concrete.

In [S&L 2003] a correlation between the maximum receiver rating P_t and tower height h is described:

$$h = 29.1 + 0.51129589 \cdot P_{t,rec} - 0.0088703442 \cdot P_{t,\ rec}^{1.5} + 32801.719 \cdot P_{t,rec}^{-2}$$

Equation 9-1: Calculation for tower height for central receiver solar thermal power station [S&L 2003]

The maximum receiver rating is indicated with 1,400 MW_t. Then the tower height of the 220 MW plant is approximately 280 m. For the calculation it is assumed that the tower is made from steel reinforced concrete.

The absorber of the volumetric air receiver of the 10 MW_e plant is made of approximately 1,500 hexagonal modules of wire mesh [Romero 2000]. It is assumed that the volumetric receiver is made from stainless steel. The weight of a 380 MW_t air receiver is indicated with about 2,500 t [Stine 1995]. The capacity of a receiver depend on the surface area of the wire mash. Therefore the size and as a result the weight of the receiver can be scaled linearly with the required capacity. The thermal power output of the 220 MW_e plant described in [S&L 2003] is indicated with 1400 MW_t. The average incident flux into the receiver of the 220 MW_e plant is indicated with 0.8 MW/m^2 and the receiver area is indicated with 1,990 m^2 which result to about 1592 MW_t. Then the stainless steel requirement is some 10.500 t or 48 kg/kW_e.

The material requirement for the power block has been derived from an 80 MW_e plant described in [Wuppertal 1996]. The material requirement for the power plant has been scaled up by

$$m(P_2) = m(P_1) \cdot \left(\frac{P_2}{P_1} \right)^{0.7}$$

Equation 9-2: Scale up of mass estimation for a turbine power plant

where:

P_1 Plant with electricity output P_1

P_2 Plant with electricity output P_2

m material requirement

Table 9-18 and Table 9-19 show the input and output data for a solar thermal power plant with central receiver and thermal storage. The thermal storage is sufficient for 13 hours of full load operation. For the storage so-called "solar salt" is used which consists of a mixture of 60% sodium nitrate ($NaNO_3$) and 40% potassium nitrate (KNO_3).

	Input	Output
Solar power [kWh/kWh]	1.00	-
Electricity [kWh]	-	1.00
Steel [kg/kW$_e$]	695	-
Stainless steel	48	-
Glass [kg/kW$_e$]	145	-
Concrete [kg/kW$_e$]	2231	-
$NaNO_3$ [kg/kW$_e$]	209	-
KNO_3 [kg/kW$_e$]	139	-
Rock wool [kg/kW$_e$]	0.35	-
Copper [kg/kW$_e$]	1.13	-
Aluminum [kg/kW$_e$]	0.71	-
Lead [kg/kW$_e$]	0.13	-
Plastics [kg/kW$_e$]	0.97	-

Table 9-18: Input and output data for a solar power station (central receiver) including thermal storage (irradiation: 1,800 kWh/m^2/a)

	Input	Output
Solar power [kWh/kWh]	1.00	-
Electricity [kWh]	-	1.00
Steel [kg/kW$_e$]	466	-
Stainless steel	48	-
Glass [kg/kW$_e$]	90	-
Concrete [kg/kW$_e$]	1,625	-
$NaNO_3$ [kg/kW$_e$]	209	-
KNO_3 [kg/kW$_e$]	139	-
Rock wool [kg/kW$_e$]	0.35	-
Copper [kg/kW$_e$]	1.13	-
Aluminum [kg/kW$_e$]	0.71	-
Lead [kg/kW$_e$]	0.13	-
Plastics [kg/kW$_e$]	0.97	-

Table 9-19: Input and output data for a solar power station (central receiver) including thermal storage (irradiation: 2,900 kWh/m^2/a)

The plant achieves an equivalent full load period of approximately 6,400 hours per year. To elevate the equivalent full load period to approximately 8,400 hours per year a hydrogen storage has been added.

b) Electricity storage via hydrogen

The efficiency of the electrolysis has been assumed to be 65% and the efficiency of the hydrogen fueled combined cycle gas turbine (CCGT) power plant has been assumed to be 55%. The lifetime of the solar thermal power plant is assumed to be 30 years.

	Input	Output
Electricity [kWh/kWh_{GH2}]	1.538	-
Water [kg/kWh_{GH2}]	0.27	-
GH_2 [kWh]	-	1.00
Steel [kg/kW_{GH2}]	4.6	-

Table 9-20: Input and output data for an electrolyzer unit with a capacity of 2.3 MW_{H2} [GHW 2001]

The equivalent full load period of the electroyzer is 6,150 hours per year. The lifetime is assumed to be 30 years.

Maximum pressure	2.0 MPa
Minimum pressure	0.2 MPa
Net storage capacity	148,000 kWh H_2
Steel requirement	158,000 kg

Table 9-21: Technical data of a typical spherical pressure vessel a volume of 3,000 m^3

For the calculation of the GHG emissions and energy requirements for the supply of electricity from solar thermal power plants 50 annual full load cycles have been assumed for the H_2 storage. The lifetime is assumed to be 30 years.

	Input	Output
GH_2 [kWh/kWh_{GH2}]	1.818	-
Electricity [kWh]		1.000
Steel [kg/kW_e]	25	-
Cement [kg/kW_e]	75	-

Table 9-22: Input and output data for the CCGT [GEMIS 2002]

The equivalent full load period of the CCGT is approximately 2,300 hours per year, the lifetime is 30 years. In the base load scenarios some 73% of the electricity is supplied directly by the solar thermal power plant whereas 27% is derived from the hydrogen storage.

c) High voltage direct current (HVDC) transmission

For electricity generated by solar thermal power plants located in North Africa, high voltage direct current (HVDC) facilities are applied for power transmission to Europe. The wires for HVDC transmission lines generally are of AlSt564/72 type (564 mm^2 aluminum plus 72 mm^2 steel). Table 9-23 and Table 9-24 lists the technical data and the material requirement for the HVDC transmission lines.

	Unit	Today	2030
Current density	A/mm^2	0.7	0.7
Current	A	2,000	2,000
Conductor area	mm^2	2,857	2,857
Aluminum	kg/m	6.8	6.8
Steel	kg/m	2.9	2.9
Voltage	kV	600	800
Number of bipols		2	2
Electric power	MW	4,800	6,400

Table 9-23: Technical data of the HVDC transmission line [Knies 1999]

	Unit	Today	2030
Distance transmission lines	km	2,500	2,500
Number of lines		4	4
Distance between towers	m	400	400
Number of towers		6,250	6,250
Mass of one lattice tower (steel)	t	40	40
Aluminum	kg	68,409,704	68,409,704
Steel	kg	257,221,024	257,221,024

Table 9-24: Material requirment of the the HVDC transmission lines

d) Results: LCA of solar thermal power plants with H_2 storage

Table 9-25 shows the GHG emissions and energy requirements for the supply of base load electricity from solar thermal power stations for the base load scenarios including hydrogen storage to achieve 8,400 full load hours per year year and for a solar irradiation of 1,800 kWh per m^2 and year. For the lower irradiation in Europe more heliostats are required. The energy requirement for construction increases with lower irradiation.

	Electricity mix EU-15 1999	Electricity mix EU-30 2020	"SOT breeder"
Primary energy [kWh/kWh_e]	0.0555	0.0553	0.0313
Energy payback ratio	18.0	18.1	32.0
Primary energy [kWh/kW_e]	13,980	13,930	7,880
GHG emissions [g CO_2equivalent/kWh_e]	21	21	13
GHG emissions [g/kW_e]	5,300,000	5,300,000	3,200,000
Energy payback time [a]	1.7	1.7	0.9
Efficiency electricity mix [%]	35.7	44.8	100
Energy payback time, electricity generation efficiency of reference system considered [a]	0.6	0.7	0.9

Table 9-25: Cumulative energy requirements and GHG emissions for the construction of a solar thermal plant with central receiver including thermal storage and electricity storage via H_2 (insulation:1,800 $kWh/m^2/yr$; electricity generation: 8,400 h/yr)

Table 9-26 shows the GHG emissions and energy requirements for the supply of base load electricity from solar thermal power stations for the base load scenarios including hydrogen storage to achieve 8,400 full load hours per year and for a solar irradiation of 2,900 kWh per m^2 and year. Because of the higher irradiaton less heliostats are needed and as a result less material is required.

On the other hand for the solar thermal power plants located in North Africa high voltage direct current (HVDC) transmission is required. The distance has assumed to be 2,500 km. For 2020 the losses of the HVDC transmission line have been assumed to be 2.5% per

1,000 km and the losses of the stations have been assumed to be 0.5% per station (today: 3.3% per 1,000 km and 0.7% per station).

	Electricity mix EU-15 1999	Electricity mix EU-30 2020	"SOT breeder"
Primary energy [kWh/kWh$_e$]	0.0491	0.0472	0.0235
Energy payback ratio	20.4	21.2	42.5
Primary energy [kWh/kW$_e$]	12,370	11,900	5,930
GHG emissions [g CO_2equivalent/kWh$_e$]	19	19	12
GHG emissions [g/kW$_e$]	4,830,000	4,670,000	3,020,000
Energy payback time [a]	1.5	1.4	0.7
Efficiency electricity mix [%]	35.7	44.8	100
Energy payback time, electricity generation efficiency of reference system considered [a]	0.5	0.6	0.7

Table 9-26: Cumulative energy requirements and GHG emissions for the construction of a solar thermal plant with central receiver including thermal storage and electricity storage via H_2 and including HVDC (insulation: 2,900 kWh/m^2/yr; electricity generation: 8,400 h/yr)

Without considering the reference system the energy payback time ranges between 1.4 and 1.6 years for the case when the electricity mix of 2020 is assumed for the manufacturing of the plants. If all electricity used for the manufacturing of the plants also were derived from solar thermal power plants ("SOT breeder") the energy payback time would decrease to some 0.7 to 0.9 years. Small amounts of GHGs are from processes which still uses fossil fuels e.g. from the supply of cement.

The solar thermal power plant generates electricity and as a result replaces electricity generated by fossil and nuclear power stations. Therefore in many literature sources the efficiency of the reference system is taken into account to calculate the energy payback time. The material requirement for the construction of the solar thermal plant including hydrogen storage has been kept constant. Then the energy payback time increases with increasing efficiency of the reference system when the reference system is considered.

In contrast to phtotovoltaic (see below) most of the energy requirement for the supply of construction materials required for solar thermal power plants is not electricity. It has been assumed that mainly coal is used for the production of steel also in 2020. Further the share of renwable electricity in 2020 is assumed to be 26% which is a rather conservative estimate. Therefore the GHG emissions do not decrease significantly in 2020 compared to the electricity mix of 1999.

Table 9-27 shows the energy requirement, the energy payback ratio and the energy payback period for construction of solar thermal power stations for the different base load scenorios.

	0.5 GW	5 GW	10 GW	50 GW	100 GW	500 GW
Share of electricity from North Africa [%]	0	0	0	0	0	44%
Total energy requirement [kWh/kWh]	0.0553	0.0553	0.0553	0.0553	0.0553	0.0517
Energy payback ratio	18.1	18.1	18.1	18.1	18.1	19.3
Total energy requirement [kWh/kW]	13,930	13,930	13,930	13,930	13,930	13,040
Energy payback period [a]	1.7	1.7	1.7	1.7	1.7	1.6
Efficiency electricity mix [%]	44.8	44.8	44.8	44.8	44.8	44.8
Energy payback time reference system considered [yr]	0.7	0.7	0.7	0.7	0.7	0.7

Table 9-27: Energy requirements for construction and energy payback time for the different base load scenarios including H_2 storage based on the EU electricity mix in 2020

For all scenarios except the 500 GW base load scenario the electricity generation potential from solar thermal power plants within Europe is sufficient. In case of the 500 GW base load scenorio 44% of the electricity is imported from North Africa. The higher irradiation in North Africa which leads to a lower energy requirement for the construction of heliostats is partly compensated by the installation of the HVDC transmission lines. The rounded number for the energy payback period is close to the other base load scenarios (1.6 years versus 1.7 years).

It has to be noted that a scenario where all electricity is generated from one electricity source is extremely unrealistic. In reality allways mixture of different electricity sources would contribute to the electricity supply. In case of a fully renewable electricity supply the electricity mix would probably consist of all renewable energy sources such as hydro power, wind power, biomass, geothermal and solar.

9.2.6 Non-base load scenario: Live-cycle analysis of PV plants

For the non-base load scenarios photovoltaic (PV) plants are used. Figure 9-8 shows the different steps of a PV chain beginning from the arenaceous sand to the electricity output.

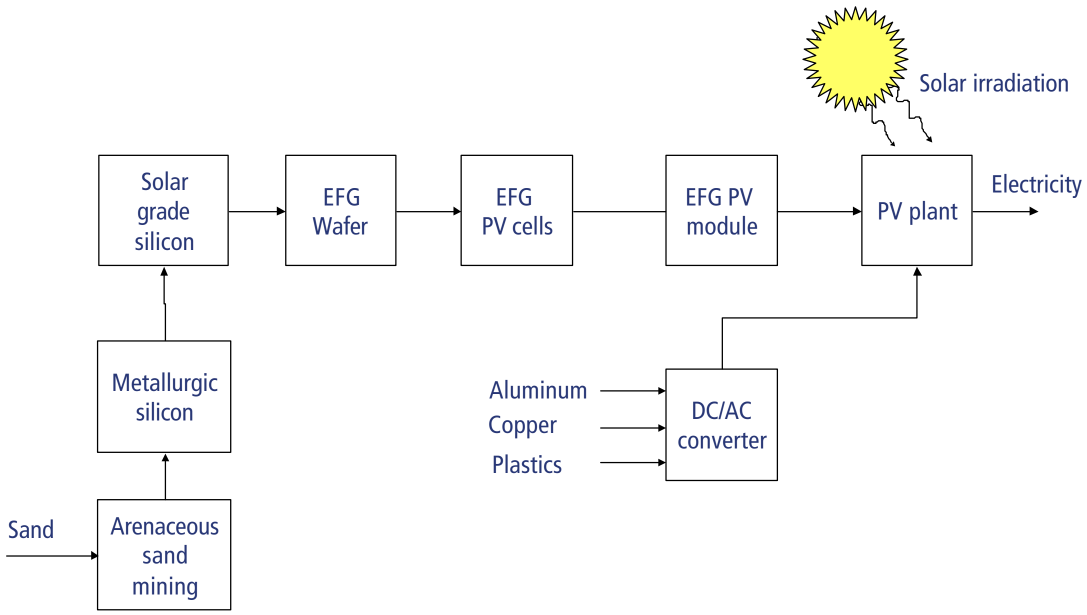

Figure 9-8: Process chain analysis of PV plants

The electricity is stored via hydrogen. The hydrogen storage system consists of the electrolyzers, the spherical pressure vessels and a combined cycle gas turbine (CCGT) power plant.

a) Mono crystalline modules

Mono crystalline photovoltaic modules are generally derived from Czochralski (CZ) grown silicon. Today electron grade silicon is used for the Czochralski process. In the near future also solar grade silicon will be used as feedstock.

	Input	Output
Solar power [kWh/kWh]	1.000	-
Electricity [kWh]	-	1.000
Aluminum [kg/kW$_p$]	38	-
Mono crystalline PV module [kg/kW$_p$]	105	-
DC/AC inverter [kg/kW$_p$]	14.2	-

Table 9-28: Input and output data for PV plants employing mono modules with mono crystalline silicon cells [GEMIS 2002], [Solarfabrik 1996]

	Input	Output
Electricity [kWh/kg]	2.1	-
Aluminum [kg/kg]	0.053	-
Flat glass [kg/kg]	0.786	-
LDPE [kg/kg]	0.101	-
Mono crystalline PV cells [kg/kg]	0.069	-
Mono crystalline PV module [kg]	-	1.000

Table 9-29: Input and output data for mono crystalline PV modules [GEMIS 2002]

	Input	Output
Electricity [kWh/kg]	142.4	-
HF [kg/kg]	0.19	-
Liquid nitrogen [kg/kg]	125	-
NaOH [kg/kg]	1.06	-
Ag [kg/kg]	0.05	-
Mono crystalline silicon wafer [kg/kg]	1.085	-
Mono crystalline PV cells [kg]	-	1.000

Table 9-30: Input and output data for mono crystalline PV cells [GEMIS 2002]

In [GEMIS 2002] data supplied by [KfA 1992] has been used. Meanwhile significant improvements concerning the electricity consumption of the manufacturing plants have been achieved.

	Input	Output
Electricity [kWh/kg]	38.6	-
HF [kg/kg]	0.19	-
Liquid nitrogen [kg/kg]	125	-
NaOH [kg/kg]	1.06	-
Ag [kg/kg]	0.05	-
Mono crystalline silicon wafer [kg/kg]	1.085	-
Mono crystalline PV cells [kg]	-	1.000

Table 9-31: Input and output data for mono crystalline PV cells [GEMIS], [Jungbluth 2000]

Mono crystalline silicon wafers are produced by the Czochralski technique. This consists of dipping a monocrystalline seed into molten polycrystalline. Once the seed is removed a monocrystalline or single-crystalline crystal ingot is formed. Then the ingot is sawed into wafers which are used for the production of mono crystalline photovoltaic cells. Table 9-32 shows the input and output data for the manufacture of mono crystalline silicon wafers.

	Input	Output
Electricity [kWh/kg]	213.6	-
Argon [kg/kg]	5.146	-
Sand [kg/kg]	0.874	-
Electron grade silicon [kg/kg]	2.008	-
Mono crystalline silicon wafer [kg]		1.000

Table 9-32: Input and output data for mono crystalline wafer [GEMIS 2002]

As mentioned above alternatively so-called “solar grade” silicon can be used.

b) Poly-crystalline modules and EFG modules

Polycrystalline silicon is manufactured from a block of polycrystalline silicon which is sliced to produce the size of wafer required. Unlike monocrystalline cells the atomic structure of polycrystalline is not regularly ordered. Polycrystalline consists of small grains of monocrystalline spread throughout the polycrystalline. This means that as the flow of current or electrons is reduced thus the efficiency of polycrystalline is lower than that of monocrystalline cells.

Silicon wafers for photovoltaic cells alternatively can be manufactured using a ribbon growth method where silicon is grown as wafers or sheets which are around the same thickness as that necessary for PV cell manufacture. Then silicon losses from sawing can be avoided. One ribbon growth method is the "Edge-defined Film-fed Growth" (EFG) process. The efficiency of photovoltaic modules made from EFG silicon is close to that of photovoltaic modules made from multy crystalline silicon photovoltaic cells.

The area of one module is 0.6 m^2. The electricity output (DC) per module is 67.5 W [Solarfabrik 1996]. The performance ratio of the PV plant is assumed to be 75%. As a result 20 modules are required for 1 kW_{peak} AC. The mass of one module is 6.5 kg. As a result 130 kg EFG modules has to be installed for 1 kW_{peak} AC. For the installation of the modules on the roofs of buildings some additonal material is required (mainly aluminium).

	Input	Output
Solar power [kWh/kWh]	1.000	-
Electricity [kWh]	-	1.000
Aluminum [kg/kW_p]	38	-
EFG PV module [kg/kW_p]	130	-
DC/AC inverter [kg/kW_p]	14.2	-

Table 9-33: Input and output data for PV plants employing EFG modules [GEMIS 2002], [Solarfabrik 1996

The equivalent full load period for the PV plants installed in the south of Europe is assumed to be approximately 1,300 kWh per kW of installed power.

	Input	Output
Aluminum [kg/kg]	0.24	-
Copper [kg/kg]	0.39	-
Plastics (HDPE) [kg/kg]	0.37	-
DC/AC inverter [kg/kg]		1.00

Table 9-34: Input and output data for the production of DC/AC converters [Solarfabrik 1996]

The thickness of photovoltaic cells made from EFG silicon are 300 µm when todays' EFG technology is employed [Solarfabrik 1996], [[FVS 2000]. Table 9-35 shows the input and output data for the manufacture of photovoltaic modules made from EFG cells. The electricity consumption has been reduced significantly (Mono crystalline PV moduels: 2.1 kWh_e/kg) compared to the electricity consumption data for mono crystalline photovoltaic modules supplied by [GEMIS 2002]. The reason is that the data in [GEMIS 2002] do not consider the improvements which meanwhile has been achieved. The electricity consumption indicated for the production of EFG photovoltaic modules has been derived from existing factories.

	Input	Output
Electricity [kWh/kg]	0.43	-
Aluminum [kg/kg]	0.053	-
Flat glass [kg/kg]	0.786	-
LDPE [kg/kg]	0.101	-
EFG PV cells [kg/kg]	0.052	-
EFG PV module [kg]	-	1.000

Table 9-35: Input and output data for EFG PV modules [GEMIS 2002], [Solarfabrik 1996]

For the production of photovoltaic cells also improvements concerning the electricity have been achieved.

	Input	Output
Electricity [kWh/kg]	22	-
HF [kg/kg]	0.19	-
Liquid nitrogen [kg/kg]	125	-
NaOH [kg/kg]	1.06	-
Ag [kg/kg]	0.05	-
EFG silicon wafer [kg/kg]	1.075	-
EFG PV cells [kg]	-	1.000

Table 9-36: Input and output data for EFG PV cells [GEMIS 2002], [Solarfabrik 1996]

	Input	Output
Electricity [kWh/kg]	135	-
Argon [kg/kg]	5.146	-
Sand [kg/kg]	0.874	-
Solar grade silicon [kg/kg]	1.111	-
EFG silicon wafer [kg]		1.000

Table 9-37: Input and output data for EFG wafer [GEMIS 2002], [Solarfabrik 1996]

c) Silicon production

Silicon photovoltaic cells can be made from so-called "electron grade" silicon or from so-called "solar grade" silicon. Until now silicon photovoltaic cells (mon crystalline as well as poly crystalline and EFG silicon cells) are made from electroc grade silicon because the silicon production plants mainly have delivered silicon for the semiconductor industry.

For the production of electron grade silicon from metallurgic silicon (purity > 98%) the silicon is grinded and subsequently converted to tri-chlorine-silan gas ($SiHCl_3$) in a fluidised bed reactor according to the following reaction:

$$4\ Si + 12\ HCl \Rightarrow 4\ SiHCl_3 + 4\ H_2$$

The reaction is exothermal and is carried out at about 300 to 400°C. The impurities are removed as $FeCl_2$, $AlCl_3$, $CaCl_2$, BCl_3, $AsCl_3$ and PCl_3 and $POCl_3$. After romoval of impurities the $SiHCl_3$ is converted back to silicon at a temperature of approximately 950°C:

$$4\ SiHCl_3 \Rightarrow Si + 3\ SiCl_4 + 2\ H_2$$

The by-product tetra-chlorine-silan (SiCl4) can be exported for the production of silicon dioxide (SiO_2) or can be converted to tri-clorine-silan ($SiHCl_3$) at a temperature of 1,200°C:

$$3\ SiCl_4 + 3\ H_2 \Rightarrow 3\ SiHCl_3 + 3\ HCl$$

The semiconductur industry needs a very pure silicon material. The photovotaic industry mainly gets the fraction of the output of the silicon processing plants which is not pure enough for the semiconductor industry. In the near future it can be expected that silicon production plants dedicated for the production of silicon for PV plants will be built. Therefore for the different non-base load scenarios solar grade silicon has been assumed. The discussion of the energy requirement for the production of photovoltaic cells derived from electron grade silicon are only for comparison.

	Input	Output
Electricity [kWh/kg]	24.85	-
Heat [kWh/kg]	-	99.99
Metallurgic silicon [kg/kg]	6.10	-
Electron grade silicon [kg]	-	1.00

Table 9-38: Input and output data for the production of electron grade silicon [GEMIS 2002]

Excess heat of the process heat is exported.

Since the production of electron grade silicon is very energy intensive and on the other hand for solar applications the purity requirment is lower new less energy intensive production methods for solar grade silicon has been developed. The production of solar grade silicon is carried out in a different way. The metallurgical grade silicon is refined in the molten state by adding moist argon and subsequently directional solidification [Chandra et al 2001], [NREL 2001], [Geerligs et al 2002]. Table 9-39 shows the input and output data for the production of solar grade silicon from metallurgic silicon.

	Input	Output
Heat [kWh/kg]	30	-
Metallurgic silicon [kg/kg]	1.25	-
Solar grade silicon [kg]		1.00

Table 9-39: Input and output data for the production of solar grade silicon [ESU 2000]

Both for electron grade and for solar grade silicon metallurgical grade silicon is required. Metallrugical grade silicon is produced from silcon dioxide (SiO_2) via reduction with carbon.

$SiO_2 + 2\ C \Rightarrow Si + 2\ CO$

The CO is combusted. After downstream refining via adding of oxygen (O_2) the purity of the metallurgical grade silicon can be reach 99.5% . Table 9-40 shows the input and output data for the production of metallurgical grade silicon.

	Input	Output
Electricity [kWh/kg]	13.89	-
Carbon for anodes [kg/kg]	0.09	-
Hard coal [kg/kg]	0.60	-
Coke [kg/kg]	0.40	-
Liquid oxygen [kg/kg]	0.02	-
Sand [kg/kg]	2.90	-
Metallurgical grade silicon [kg]	-	1.00

Table 9-40: Input and output data for the production of metallurgical grade silicon [GEMIS 2002]

The sand mainly consists of SiO_2 which is reduced to metallurgical silicon (Si). The sand used for the production of metallurgical silicon is extracted via surface mining.

	Input	Output
Electricity [kWh/kg]	0.0025	-
Mechanical work [kWh/kWh]	0.0050	-
Material source [kg/kg]	1.00	-
Sand [kg]	-	1.00

Table 9-41: Input and output data for the supply of sand via surface mining [GEMIS 2002]

The mechanical work is supplied by a diesel engine which achieves an efficiency of 30%.

d) Results: PV plant with mono crystalline modules

The useful lifetime of photovoltaic power plants employing mono crystalline silicon cells is indicated with 30 years [GEMIS 2002]. The equivalent full load period is assumed to be 1,300 hours per year.

	Electricity mix EU-15 1999	Electricity mix EU-30 2020	“PV breeder”
Primary energy [kWh/kWh_e]	0.346	0.269	0.103
Primary energy [kWh/kW_p]	13,500	10,470	4,020
GHG emissions [g CO_2equivalent/kWh_e]	65	52	12
GHG emissions [g/kW_p]	2,520,000	2,020,000	490,000
Energy payback time [a]	10.4	8.1	3.1
Efficiency electricity mix [%]	35.7	44.8	100.0
Energy payback time, electricity generation efficiency of reference system considered [a]	3.7	3.6	3.1

Table 9-42: Cumulative energy requirements and GHG emissions for the construction of a PV plant employing mono crystalline silicon cells from electron grade silicon without considering electricity storage (electricity generation: 1,300 kWh/kW_{peak})

The share of renewable electricity of the EU-15 electricity mix in 1999 was approximately 14%. The share of renewable electricity of the EU-30 electricity mix in 2020 has been assumed to be some 26% which can be considered as a conservative assumption. According to the EU Directive 2001/77/EC [EU 2001] the share of renewable electricity within the EU-25 has to reach at least 21% until 2010.

Most of the energy used for the manufacture of a photovoltaic power plant is electricity. Therefore the energy payback time decreases with increasing electricity generation efficiency for the case when no reference system is considered.

“PV breeder” means that all electricity required for the supply of construction material are also generated with PV. The different electricity generation scenarios show the influence of the electricity source on the energy requirement for the construction of the PV power plant.

A further reduction of the energy requirement for the PV power plant construction can be achieved when the photovoltaic cells are made from solar grade silicon instead of electron grade silicon (Table 9-43).

	Electricity mix EU-15 1999	Electricity mix EU-30 2020	"PV breeder"
Primary energy [kWh/kWh$_e$]	0.252	0.206	0.133
Primary energy [kWh/kW$_p$]	9,840	8,030	5,200
GHG emissions [g CO_2equivalent/kWh$_e$]	46	38	5
GHG emissions [g/kW$_p$]	1,790,000	1,480,000	200,000
Energy payback time [a]	7.6	6.2	4.0
Efficiency electricity mix [%]	35.7	44.8	100
Energy payback time, electricity generation efficiency of reference system considered [a]	2.7	2.8	4.0

Table 9-43: Cumulative energy requirements and GHG emissions for the construction of a PV plant employing mono crystalline silicon cells from solar grade silicon without considering electricity storage (electricity generation: 1,300 kWh/kW$_{peak}$)

If all electricity required for the manufacture of the PV plant is derived from the PV plant itself ("PV breeder") the cumulative energy demand for the manufacturing is slightly higher in case of solar grade silicon than in case when electron grade silicon is used. The reason is that there is a large heat credit in case of the electron grade silicon production stage which influenes the cumulative energy demand significantly in the case when the PV plant is manufactured with PV electricity.

If the the reference system were included the energy payback time increases with higher efficiency of the reference system for the case when solar grad silicon is used for the photovoltaic cells. The production of solar grade silicon mainly heat is required. The efficiency of heat generation is 85%.

e) Results: PV plants with EFG modules

The useful lifetime of photovoltaic power plants employing EFG silicon derived cells has been assumed to be 30 years. Table 9-44 shows the cumulative energy requirements and GHG emissions for the construction of a photovoltaic power plant employing EFG cells made from electron grade silicon.

	Electricity mixEU-15 1999	Electricity mixEU-30 2020	"PV breeder"
Primary energy [kWh/kWh_e]	0.184	0.145	0.058
Primary energy [kWh/kW_p]	7,180	5,650	2,260
GHG emissions [g CO_2equivalent/kWh_e]	36	29	8
GHG emissions [g/kW_p]	1,380,000	1,140,000	310,000
Energy payback time [a]	5.5	4.3	1.7
Efficiency electricity mix [%]	35.7	44.8	100
Energy payback time, electricity generation efficiency of reference system considered [a]	2.0	1.9	1.7

Table 9-44: Cumulative energy requirements and GHG emissions for the construction of a PV plant employing EFG silicon cells from electron grade silicon without considering electricity storage (electricity generation: 1,300 kWh/kW_{peak})

Table 9-45 shows the cumulative energy requirements and GHG emissions for the construction of a photovoltaic power plant employing EFG cells made from solar grade silicon. The equivalent full load period is assumed to be 1,300 kWh per year.

	Electricity mix EU-15 1999	Electricity mix EU-30 2020	"PV breeder"
Primary energy [kWh/kWh$_e$]	0.164	0.135	0.073
Primary energy [kWh/kW$_p$]	6,380	5,280	2,850
GHG emissions [g CO_2equivalent/kWh$_e$]	31	26	4
GHG emissions [g/kW$_p$]	1,200,000	1,010,000	170,000
Energy payback time [a]	4.9	4.1	2.2
Efficiency electricity mix [%]	35.7	44.8	100
Energy payback time, electricity generation efficiency of reference system considered [a]	1.8	1.8	2.2

Table 9-45: Cumulative energy requirements and GHG emissions for the construction of a PV plant employing EFG silicon cells from solar grade silicon without considering electricity storage (electricity generation: 1,300 kWh/kW$_{peak}$)

f) Comparison and selection Non-base load

Figure 9-9 shows a comparison of the energy requirement for the construction of PV plants depending on the photovoltaic cell technology, the silicon production method and the used electricity for the manufacturing processes.

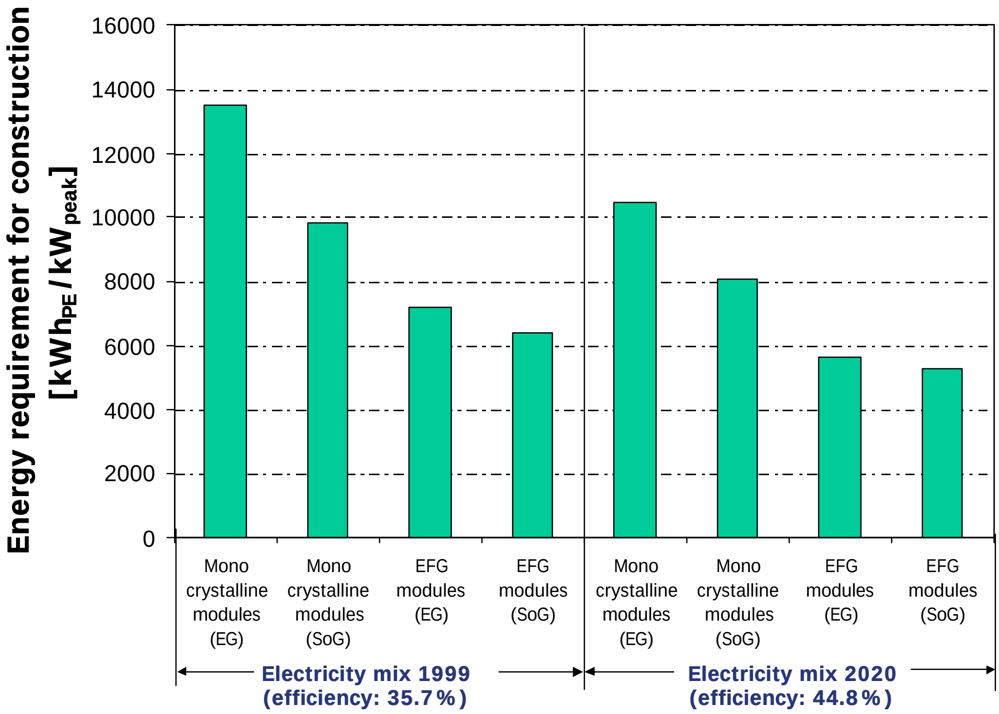

Figure 9-9: Energy requirement for the construction of one kW$_{peak}$ depending on different PV cell technologies and different electricity mixes for the manufacturing processes

In this study only crystalline silicon cells has been considered. For PV plants employing thin film modules the cumulative energy requirement can be reduced further. For the non-base load scenarios PV plants employing EFG PV modules made from solar grade silicon has been used.

g) Results: LCA of PV plants with H_2 storage

For the different non-base load scenarios PV modules with EFG silicon cells made from solar grade silicon has been assumed. Table 9-46 shows the GHG emissions and the energy requirements for the manufacture of PV plants employing EFG cells from solar grade silicon including the H_2 storage whereas it is assumed that all electricity generated by the PV plant is converted to hydrogen and subsequently converted back to electricity. The efficiency of the electrolysis is assumed to be 65% and the efficiency of the combined cycle gas turbine (CCGT) power plant is assumed to be 55%.

Table 9-46 shows an example for the energy requirement and the GHG emissions for the construction of the supply of electricity from PV plants employing EFG silicon modules made from solar grade silicon including the electricity storage via hydrogen.

	Electricity mix EU-15 1999	Electricity mix EU-30 2020	"PV breeder"
Primary energy [kWh/kWh$_e$]	0.360	0.299	0.277
Primary energy [kWh/kW$_p$]	14,020	11,650	10,810
GHG emissions [g CO_2equivalent/kWh$_e$]	69	59	11
GHG emissions [g/kW$_p$]	2,680,000	2,280,000	430,000
Energy payback time [a]	10.8	9.0	8.3
Efficiency electricity mix [%]	35.7	44.8	100
Energy payback time, electricity generation efficiency of reference system considered [a]	3.9	4.0	8.3

Table 9-46: Cumulative energy requirements and GHG emissions for the construction of a PV plant employing EFG silicon cells from solar grade silicon including electricity storage via H_2 (share of electricity via H_2: 36%, 50 full load loading/unloading cycles of the H_2 storage)

The hydrogen is storage in spherical pressure vessels (see 9.2.5 LCA of solarthermal power stations for the base load scenarios). The electricity mix used in the processes for the supply of construction strongly influences the result.

In case of the 0.5, 5 GW and 10 GW non-base load scenarios described in WP2 all electricity (100%) is generated via the hydrogen pathway from PV electricity. In case of the largest non-base load scenario 64% of the electricity is generated via the hydrogen pathway and 36% is derived directly from the PV plant..

It has been assumed that the stored hydrogen is used for electricity generation in existing CCGT power plants which are used for peak load electricity supply (equivalent full load period 2,300 hours per year).

Table 9-47 shows the energy requirement for the construction of the plants and the energy payback time.

	0.5 GW	5 GW	10 GW	50 GW	100 GW	150 GW
Number of loading/unloading cycles H_2 storage	1	1	1	10	20	50
Share direct PV electricity [%]	0	0	0	18	32	36
Total energy requirement [kWh/kWh]	0.740	0.740	0.740	0.368	0.316	0.299
Energy payback ratio	1.4	1.4	1.4	2.7	3.2	3.3
Total energy requirement [kWh/kW_{peak}]	28,860	28,860	28,860	14,350	12,330	11,650
Energy payback period [yr]	22.2	22.2	22.2	11.0	9.5	9.0
Efficiency reference system [%]	0.448	0.448	0.448	0.448	0.448	0.448
Payback time reference system considered [yr]	9.9	9.9	9.9	4.9	4.2	4.0

Table 9-47: Energy requirements for construction and energy payback time for the different non-base load scenarios including H_2 storage based on the EU electricity mix in 2020 (EFG modules made from solar grad silicon)

Table 9-48 shows a split of the energy requirement for the supply of the construction material.

	0.5 GW [kWh/kWh_e]	5 GW [kWh/kWh_e]	10 GW [kWh/kWh_e]	50 GW [kWh/kWh_e]	100 GW [kWh/kWh_e]	150 GW [kWh/kWh_e]
PV plant	0.38	0.38	0.38	0.33	0.30	0.29
H_2 storage	0.36	0.36	0.36	0.03	0.02	0.01
Total	0.74	0.74	0.74	0.37	0.32	0.30

Table 9-48: Split of energy requirements for construction for the different non-base load scenarios based on the EU electricity mix in 2020 (EFG modules made from solar grad silicon)

The "H_2 storage" includes the energy requirement for the electrolysis plant, the pressure vessels and the combined cycle gas turbine (CCGT) power plant.

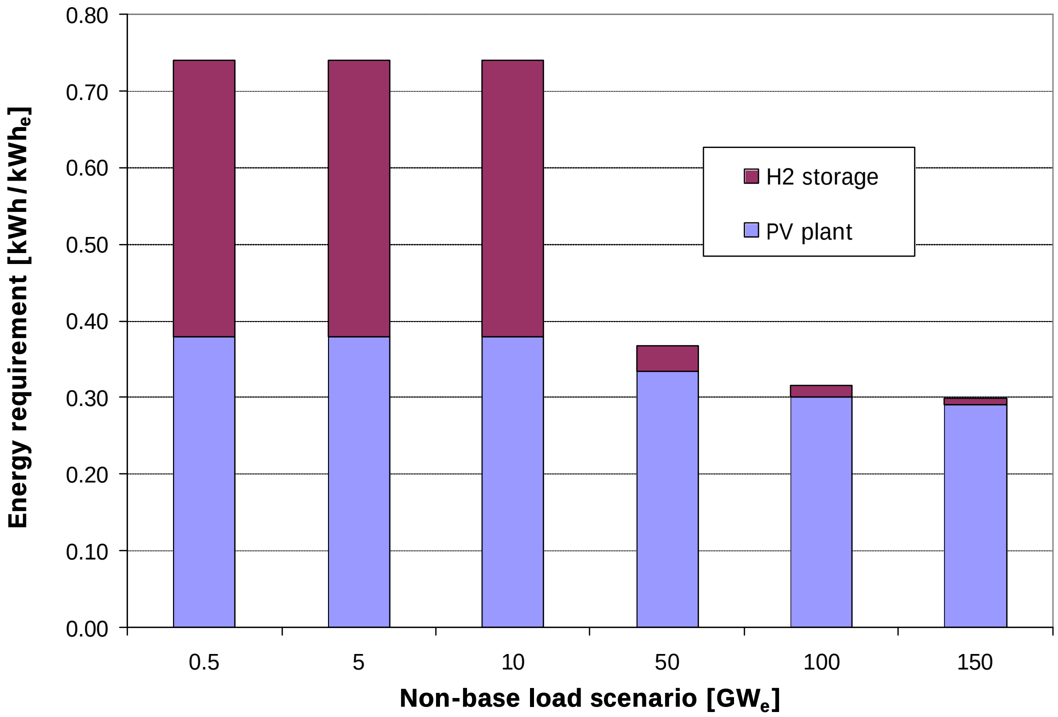

Figure 9-10: Split of energy requirement for the construction of the different non-baseload scenarios based on the EU electricity mix in 2020 (EFG modules made from solar grad silicon)

It has to be noted that these scenarios are not realistic because especially in case of the smaller scenarios up to 10 GWp the electricity can easily be absorbed from the grid. As a result no storage would be required for realistic scenarios.

Further nobody would use only one kind of renewable energy sources. There is always a mix of different renewable electricity sources. PV plants generate large amounts of electricity during summer days whereas wind power stations have their highest electricity output in winter. As a result fluctuations are compensated at a large extent by the mixture of different renewable energy sources.

Figure 9-11 shows a comparison of the energy payback time without considering the efficiency of a reference system (electricity mix) for the case when a hydrogen storage is employed and for the case of a PV plant without any electricity storage system (i.e for the case when all electricity can be absorbed by the grid).

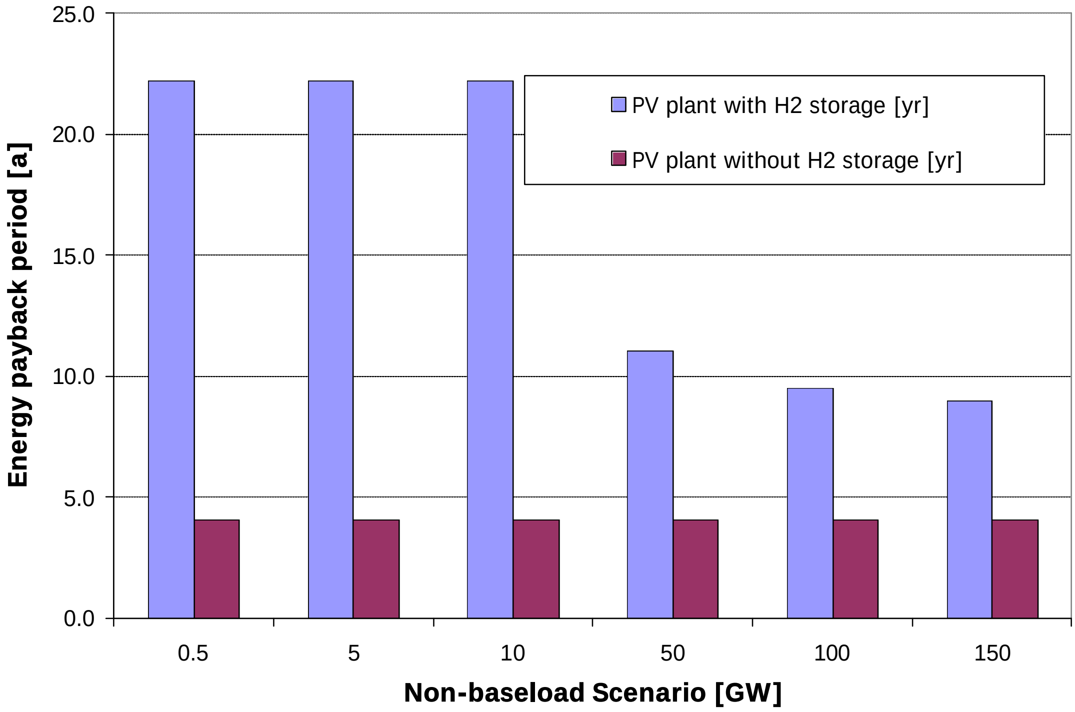

Figure 9-11: Comparison PV plant with and without H_2 storage: Energy payback period for PV plants applying EFG modules

Without any electricity storage the energy payback time is equivalent for all scenarios. Without considering the efficiency of a reference system the energy payback time would be we approximately 4.0 years. Including the efficiency of a reference system (electricity mix 2020: 44.8%) the energy payback time is approximately 1.8 years if no electricity storage were required.

9.3 Comparison of space and terrestrial power plants

Both terrestrial thermal solar power plants and space-based solar power systems (SPS) achieve a sufficient energy payback time, even in the case when no reference system is considered (worst case definition of the energy payback time). For the smallest scenario the energy payback time for SPS is significantly higher than that of terrestrial solar power including electricity storage via hydrogen. For the larger scenarios SPS has a slightly lower energy payback time (1.1 instead of 1.6 to 1.7 years).

	0.5 GW	5 GW	10 GW	50 GW	100 GW	500 GW
SOT with H_2 storage	1.7	1.7	1.7	1.7	1.7	1.6
SOT without H_2 storage	1.1	1.1	1.1	1.1	1.1	1.0
SPS	4.4	1.0	1.0	1.0	1.0	1.0

Table 9-49: Comparison terrestrial solar power versus SPS without considering the reference system

Without electricity storage the energy payback period of the solar thermal power plant with central receiver would be approximately one year.

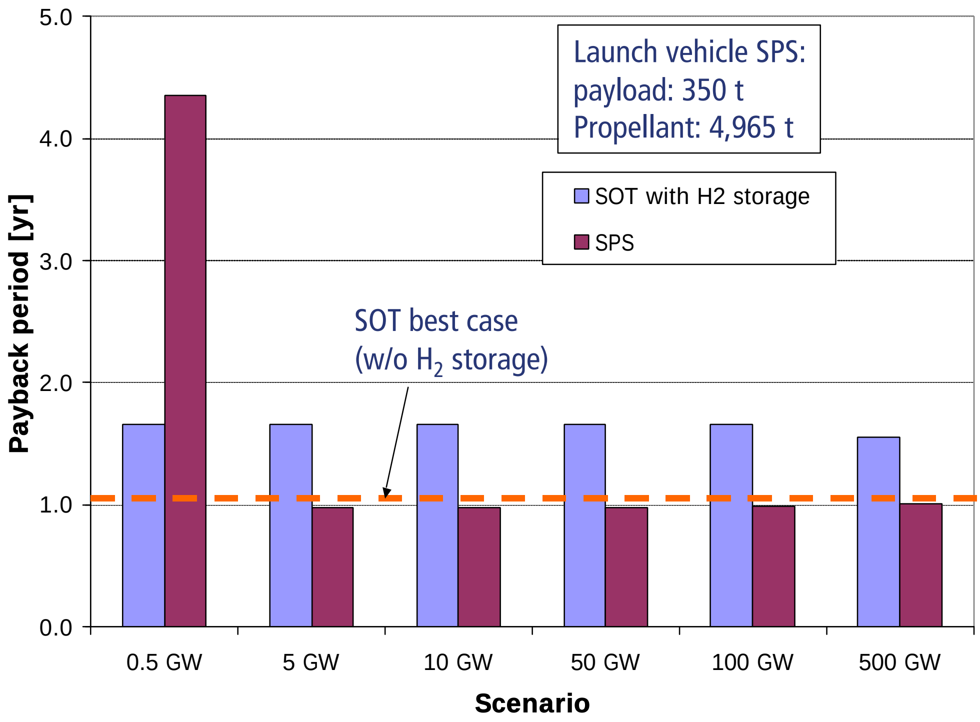

Figure 9-12: Comparison terrestrial solar power versus SPS without considering a reference system

If the reference system (replaced electricity from conventional electricity generation) are included, the energy payback time would decrease to about 0.5 years for SPS and to some 0.7 years for solar thermal plants with electricity storage via hydrogen in case of the larger scenarios (5 GW and greater).

	0.5 GW	5 GW	10 GW	50 GW	100 GW	500 GW
SOT with H_2 storage	0.7	0.7	0.7	0.7	0.7	0.7
SOT without H_2 storage	0.5	0.5	0.5	0.5	0.5	0.4
SPS	2.0	0.4	0.4	0.4	0.4	0.5

Table 9-50: Comparison terrestrial solar power versus SPS incl. considering the reference system

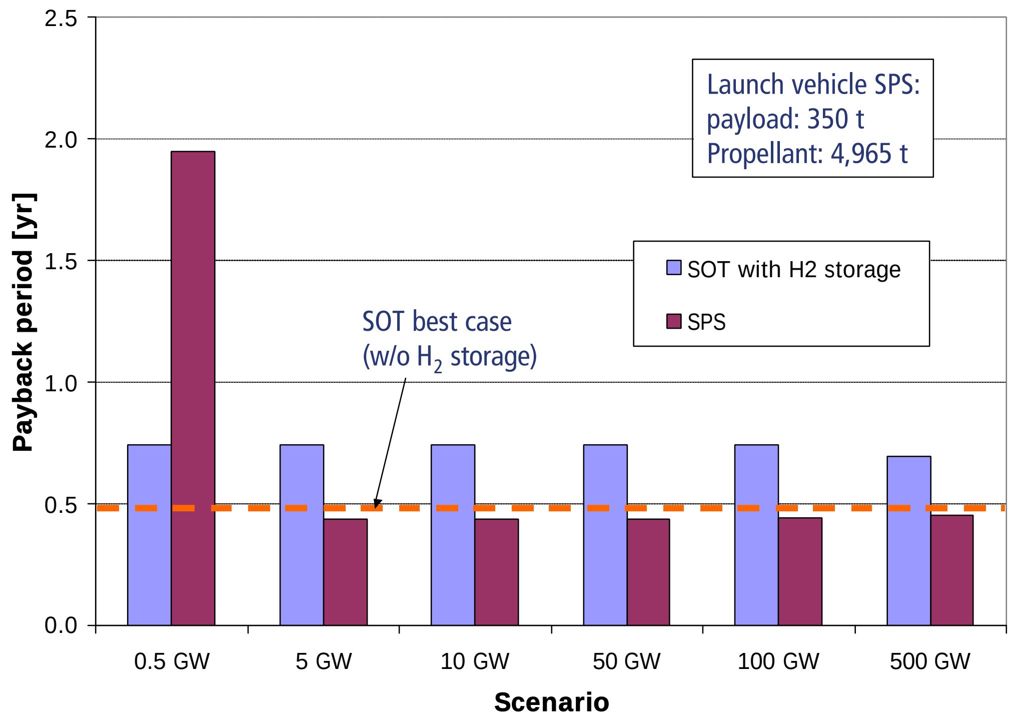

Figure 9-13: Comparison terrestrial solar power versus SPS when the reference system is considered

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 for each ton of payload. In [NASA 1997] the payload has been assumed to be 11.3 t and the propellant mass has been assumed to be 804.5 t which lead to a propellant consumption has of some 71 t for each ton of payload.

If considering the launch vehicle as described in this study's reference [NASA 1997], the energy payback time for SPS would more than double compared to the Koelle's vehicle concept (Figure 9-14).

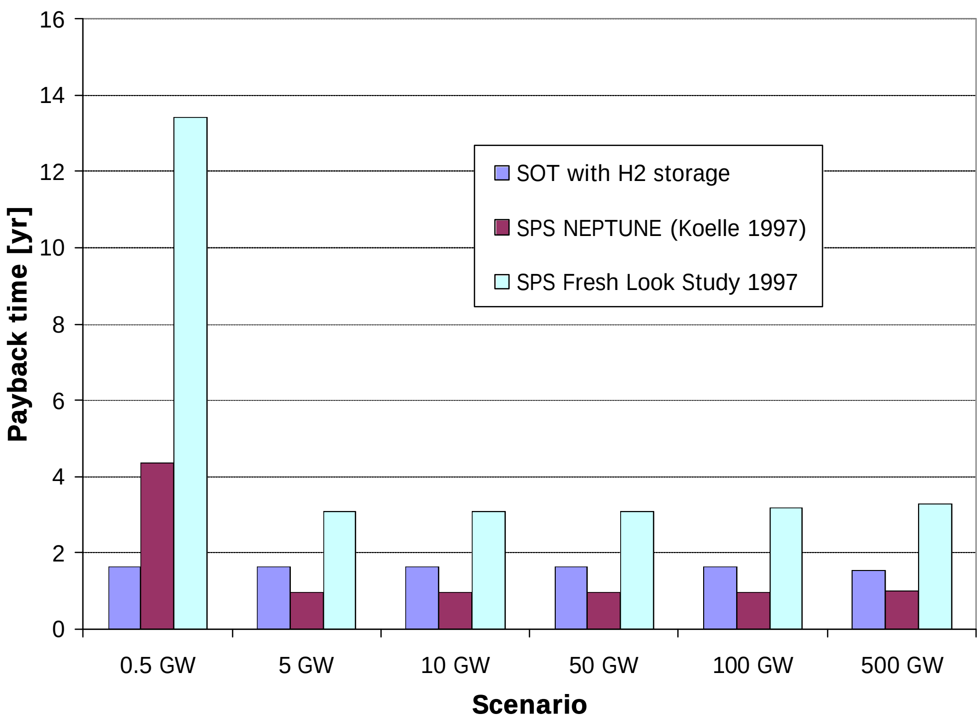

Figure 9-14: Influence of the launch vehicle on the energy payback time (without considering a reference system)

The energy backpack time of SPS concepts strongly depends on the used 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).

9.4 Discussion of net energy balance during the phase of installation

The energy pay back time is a serious parameter to be taken into account. Beyond the pay back period for an individual installation, a second constraint exists in the energy consumption of all installations during the period of growth. Starting with a single installation each year the construction of an exponentially growing number of new power plants follows, while the energy production of the already completed power plants contributes with a certain time lag (equivalent to the time of construction). During the phase of exponential growth this energy deficit (or surplus) does accumulate.

Therefore it is of some interest to look to the maximum allowable growth rates which still lead to a positive net energy balance even during the phase of expansion of installations.

Some simple relations can be found which allow to draw some general conclusions on this energy balance between energy consumption for construction of new power plants and energy supply from already completed installations. These are given in this chapter.

These comprehensive formulas use a single parameter for energy investment and construction time. However, it should be kept in mind that in reality technological improvements may reduce the energy pay back time as well as the construction time. In addition, as soon as the growth rate flattens towards the number of plants needed for repowering, the balance shifts in favor of energy production from completed installations. Therefore the results of this analysis should be seen as a lower limit to the allowed growth rates which might be shifted upwards by future learning effects.

9.4.1 Theory of energy balance during growth period

The following symbols are used in the course of this chapter:

i Suffix to describe the variable in the year i after start of construction of first installation

q Annual growth rate of scenario installations

I Total energy investment for the construction of the first installation

j Construction period of individual installations (I/j = annual energy consumption during the construction phase)

m Final year of time period under consideration

E Annual energy supply of first installation after start of operation (E and I must be given in same units, but these can be arbitrarily chosen)

$PE_m(q, E, I, j)$ Cumulative net energy balance after m years, starting with the year of the beginning of the construction of the first installation

The following Table 9-51 sketches the annual energy consumption and return for the individual years, if the growth is exponential with a constant growth rate [Wagner 1978].

Year after construction start	Energy consumption during construction	Energy production after commissioning
1	I/j	0
2	$I/j \cdot (1+q)$	0
3	$I/j \cdot (1+q)^2$	0
...	...	0
i	$I/j \cdot (1+q)^{i-1}$	0
j+1	$I/j \cdot [(1+q)^{i-1} - (1+q)^{i-1-j}]$	E
j+2	...	$E \cdot (1+q)^{i-j-1}$
....	...	...
m	$I/j \cdot [(1+q)^{m-1} - (1+q)^{m-1-j}]$	$E(1+q)^{m-j-1}$

Table 9-51: Formulae to calculate the energy effort and return in the course of installation and operation respectively

To get cumulative figures, these data can be summed up. This results in the combination of geometric progression series.

Cumulated energy balance after m years from construction start:

$$PE_m(q, E, I, j) = -\sum_{i=1}^{m} \frac{I}{j} \cdot (1+q)^{i-1} + \sum_{k=j+1}^{m} \frac{I}{j} \cdot (1+q)^{k-1-j} + \sum_{k=j+1}^{m} E \cdot (1+q)^{k-1-j} =$$

$$\ldots \quad = -\frac{I}{j} \cdot \frac{(1+q)^{m-j}}{q} \cdot \left[(1+q)^j - 1\right] + E \cdot \frac{(1+q)^{m-j} - 1}{q}$$

To keep the energy balance always positive during the phase of growth – except during the first $j+I/E$ years – implies that for any year the following relation holds:

$$E \cdot (1+q)^{i-1-j} > \frac{I}{j} \cdot \left[(1+q)^{i-1} - (1+q)^{i-1-j}\right]$$

This results in the growth limits for the scenario as:

$$q_{\max} < \left(j \cdot \frac{E}{I} + 1 \right)^{1/j} - 1$$

Any growth rate larger than q_{max} leads to a negative energy balance, any growth rate smaller q_{max} results in a positive energy balance.

Finally, the growth rate can be optimized to achieve the largest net energy supply even during the period of construction.

This results in the optimal growth rate as:

$$q_{opt} = \left[\frac{i - j - 1}{j - 1} \cdot \left(j \cdot \frac{E}{I} + 1 \right) \right]^{1/j} - 1$$

However, such a scenario has only a meaning over a well defined time period. Therefore over the introduction period of m years the optimum growth rate is given by:

$$\left. \frac{dP_m(q, E, I, j)}{dq} \right|_{q=q_{opt}} = 0$$

This results in:

$$q_{opt} = \left[\frac{m - j}{m} \cdot \left(j \cdot \frac{E}{I} + 1 \right) \right]^{1/j} - 1$$

A growth rate larger than zero gives a second (self explaining) condition on the scenario:

$$q_{opt} > 0$$

and therefore

$$j \cdot \frac{E}{I} + 1 > \frac{m}{m - j}$$

or

$$m > j + \frac{I}{E},$$

which translates into the trivial result that the addition of new power plants must continue at least as long as the construction of the first power plant is finished plus the energy pay back time of an individual installation. Otherwise the energy balance remains negative.

9.4.2 Energy payback and scenario calculations

Using these formulas helps to calculate net energy balances and growth rates very fast. This is done in the following by using somewhat simplifying assumptions, which mainly depend in constant energy investment over the whole scenario and equal distribution of the energy requirement during the construction. The reference system (European electricity mix 2020) is not considered i.e. it is not considered that the electricity generated by the solar systems replaces primary energy required for conventional electricity generation. Therefore this concept is equivalent to a "solar breeding" concept where the energy for the construction of new power plants has to be taken from the energy output of already completed installations.

a) Solar power satellites (SPS)

Results for solar power satellites are provided in this chapter. Table 9-52summarizes the input data used in the calculation.

SPS plant	Symbol	Value
Size of unit		5 GW
Construction period	j	2 years
Energy requirement during construction	I	43 TWh
Energy production	E	43 TWh
Scenario timeline	m	25 years

Table 9-52: SPS plant assumptions for energy payback calculation

Table 9-53 shows the resulting maximum and optimum growth rates. as can be seen from the table the required installations of up to 500 GW are easily met without stressing the limits.

Results SPS	Symbol	Value
Max growth rate	q_{max}	73%
Optimum growth rate	q_{opt}	66%
Installed capacity after 25 years (q_{opt})		1,590 TW

Table 9-53: Optimum SPS growth rate for various energy payback times

To illustrate the use of the above derived formulae, the example of the SPS-scenario was investigated a bit further. In Figure 9-15 a positive energy balance during the scenario period is only achieved if the annual growth rate remains below 73 %. By far the largest gain is achieved at an optimal growth rate of 66 %. However, these figures strongly depend on the annual energy investment (which in turn depends on the construction time). For instance, if the construction time of a 5 GW unit exceeds 5 years, the maximum and optimum growth rates are strongly reduced to 43% and 37 %, respectively.

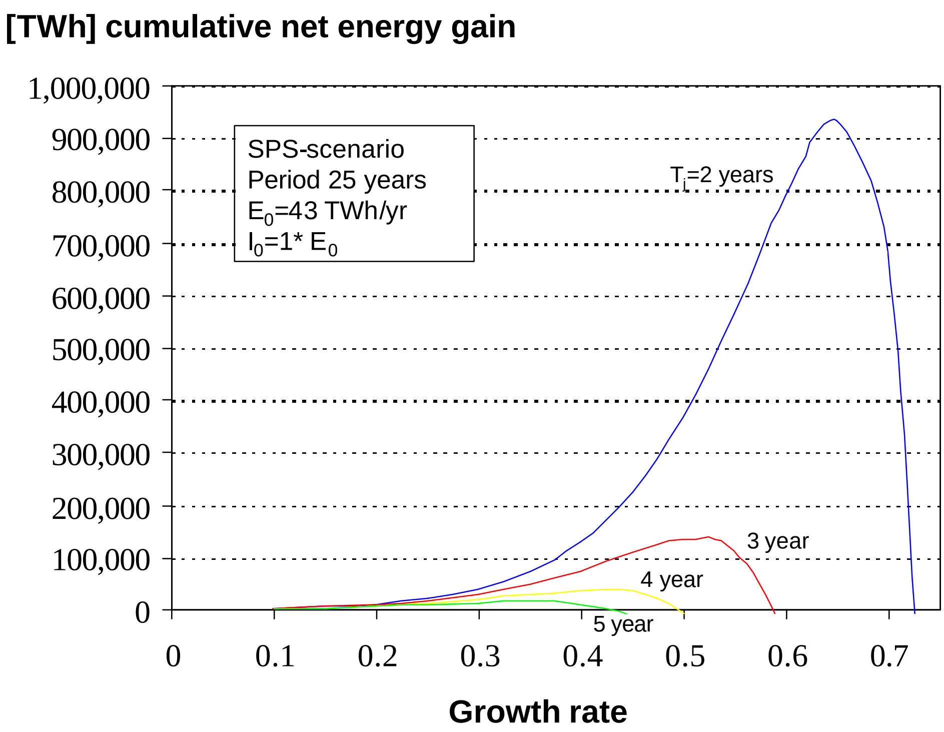

Figure 9-15: Cumulative net energy gain over 25 years time period within a SPS-growth scenario in dependence of the annual growth rate. The construction time of the individual units is changed between 2 years and 5 years.

Apart from the cumulative energy balance over the full scenario period, the energy balance of the final year might be of interest. In Figure 9-16, this is detailed even further for the scenarios with an assumed construction time of 2 years for a single unit.

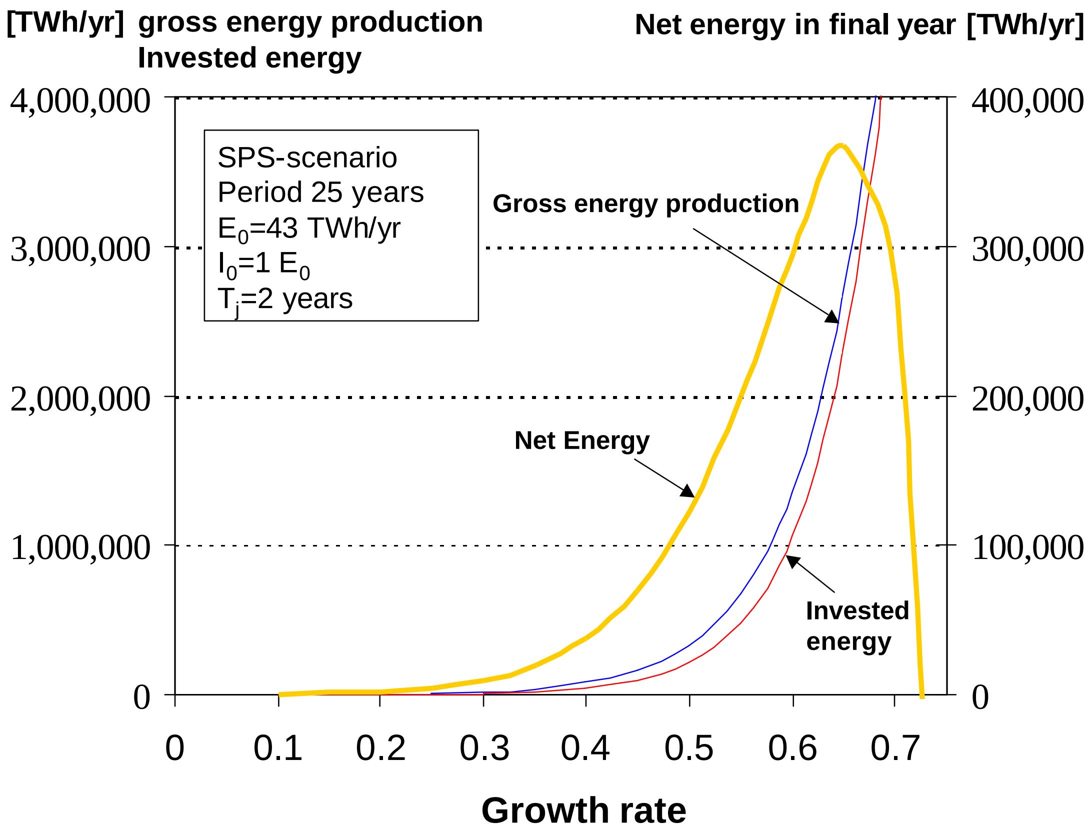

Figure 9-16: Annual energy balance for the final 25th year of the scenarios, exhibiting the net energy production as difference between the gross energy production and the energy investment for power plants which are still under construction.

Finally, Figure 9-17 details the annual energy balance over the full scenario time horizon for a scenario with the optimum growth rate of 66% per year. Gross energy production, energy investment and net energy production for the final 25th year are the same as in Figure 9-16 at a growth rate of 66%.

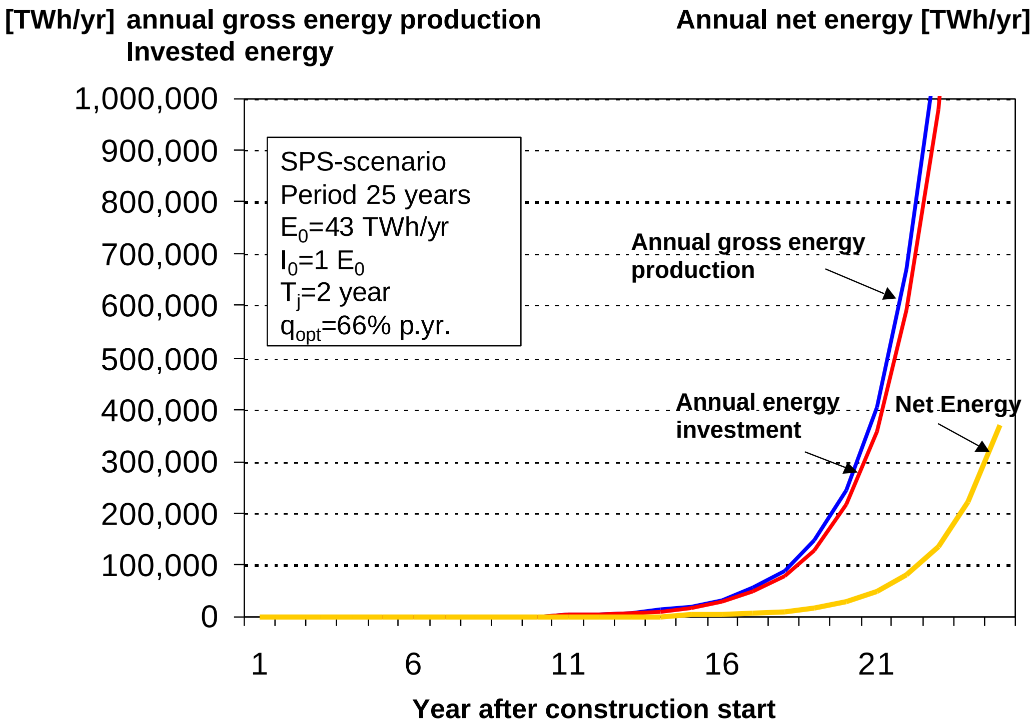

Figure 9-17: Annual energy balance of the SPS growth scenario at annual growth rate of 66 %. Shown is the annual energy consumption for power plants still under construction (red line) and the energy output of already completed power plants (blue). The thick yellow line gives the annual net energy gain as difference of these two lines.

A realistic growth scenario, of course, follows a bell shaped growth instead of exponential growth as assumed here. However, the first half of the growth might be simulated with an exponential growth scenario to check its feasibility. As soon as the growth decelerates, the net energy balance is assured anyhow, as the completion of new power plants starts to rise faster than the energy investment for further power stations which are still under construction.

b) Solar thermal (SOT)

Results for solar power satellites are provided in this chapter. Table 9-54summarizes the input data used in the calculation. Table 9-55 shows the resulting maximum and optimum growth rates.

SOT plant	Symbol	Value
Size of unit (Net power output)		108 MW
Construction period	j	1 year
Energy requirement during construction	I	1.5 TWh
Energy production per year	E	0.907 TWh/yr
Scenario timeline	m	25 years

Table 9-54: Assumed energy figures for SOT plant for energy payback calculation

With the data of Table 9-54 the following results are achieved (Table 9-55):

Results SOT	Symbol	Value
Maximum growth rate	q_{max}	60%
Optimum growth rate	q_{opt}	54%
Installed capacity after 25 years (q_{opt})		5.3 TW

Table 9-55: Optimum SOT growth rate for various energy payback times

The scenario dependent goals of up to 500 GW are easily met without touching the restrictions of a positive energy balance.

In Figure 9-18 a positive energy balance during the scenario period is only achieved if the annual growth rate remains below 60 %. By far the largest gain is achieved at an optimal growth rate of 54 %. However, these figures strongly depend on the annual energy investment (which in turn depends on the construction time). For instance, if the construction time of a 108 MW unit exceeds 2 years, the maximum and optimum growth rates are strongly reduced to 48% and 42 %, respectively.

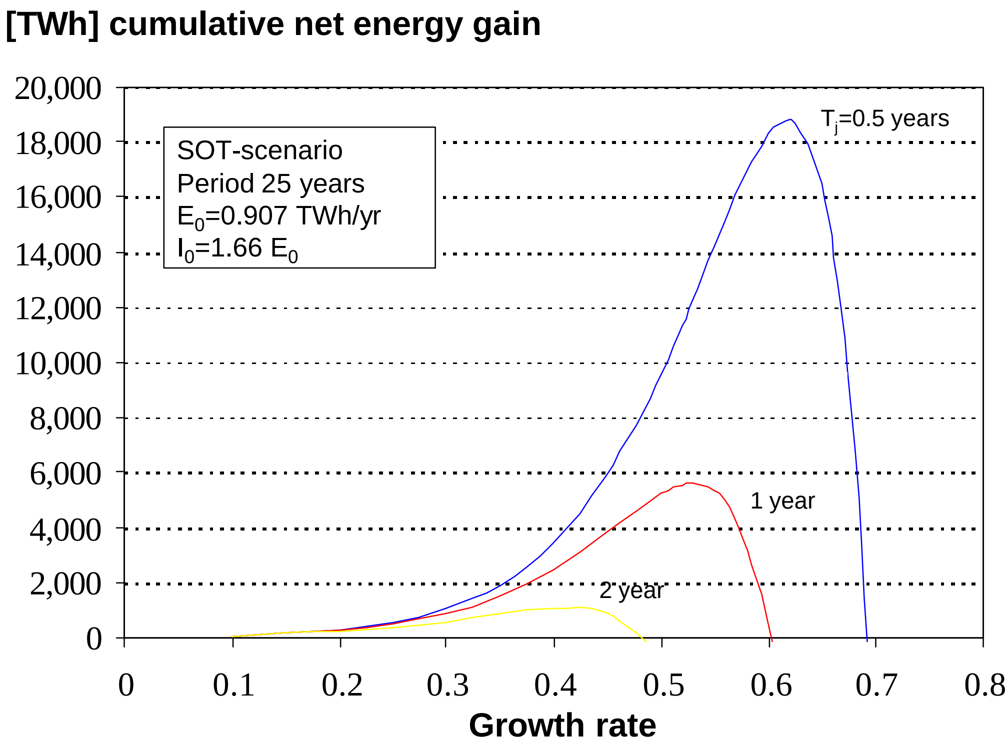

Figure 9-18: Cumulative net energy gain over 25 years time period within a SOT-growth scenario in dependence of the annual growth rate. The construction time of the individual units is changed between 0.5 years and 2 years.

Apart from the cumulative energy balance over the full scenario period, the energy balance of the final year might be of interest. In Figure 9-19, this is detailed even further for the scenarios with an assumed construction time of 1 year for a single unit.

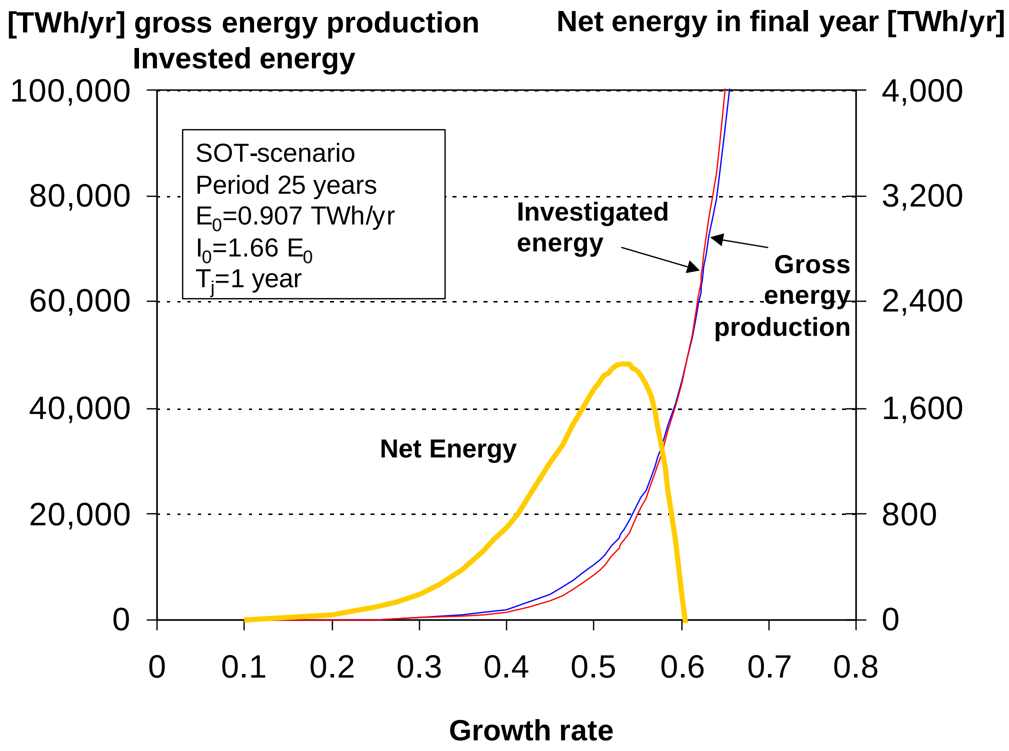

Figure 9-19: Annual energy balance for the final 25th year of the scenarios, exhibiting the net energy production as difference between the gross energy production (blue line) and the energy investment for power plants which are still under construction (red line).

Finally, Figure 9-20 details the annual energy balance over the full scenario time frame for a growth scenario with the optimum growth rate of 54% per year. Gross energy production, energy investment and net energy production for the final 25th year are the same as in Figure 9-19 at a growth rate of 54 %.

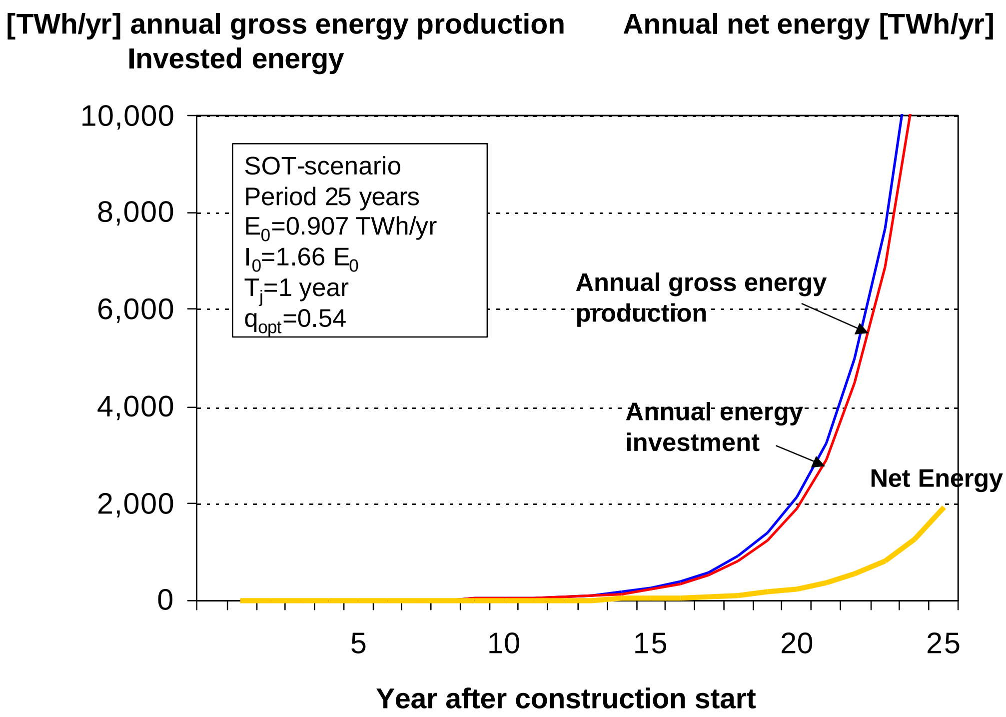

Figure 9-20: Annual energy balance of the SOT growth scenario at annual growth rate of 54 %. Shown is the annual energy consumption for power plants still under construction (red line) and the energy output of already connected power plants (blue). The thick yellow line gives the annual net energy gain as difference of these two lines.

With the help of the above derived formulae fast surveys on energy balances may be achieved to check various growth scenarios, and to test if a set power target for the final year x may be achieved with a positive energy balance over the scenario period.

A realistic growth scenario, of course, follows a bell shaped growth factor instead of constant growth as assumed here. However, the first half of the growth might be simulated with an exponential growth scenario to check its feasibility. As soon as the growth rate decelerates, the net energy balance is assured anyhow, as the completion of new power plants starts to rise faster than the energy investment for further power stations which are still under construction.

c) Photovoltaic (PV)

In 2002 the installed capacity of PV installation has already exceeded 2,200 MW [JRC 2003]. In 2003 the annual PV production has reached 750 MW [Schmela 2004]. For the calculation no hydrogen storage has taken into account because the electricity grid easily can absorb PV electricity added within the next years. Further PV plants employing "Edge-defined Film-fed Growth" (EFG) silicon photovoltaic cells employing solar grade silicon are used in order to compensate for the assumption of a constant energy effort per installation over the whole time horizon.

The production of photovoltaic modules is rather electricity intensive. Therefore a rather large share of the primary energy demand is derived from electricity generation. On the other hand PV plants generate electricity. Therefore for the calculation of the maximum growth rate and the optimum growth rate it has been assumed that all electricity required for the PV plants is generated by the PV plants itself ("PV breeder"). The efficiency of electricity generation from renewable electricity sources such as hydro power, wind power and solar power is defined to be 100%:

Table 9-56 summjarizes the input parameters for the calculation. Since photovoltaics is highly modular, any quantity could be taken as starting value (unit size). However, for small scale installations a realistic construction time is not available. Therefore the world wide annual installations of the year 2003 are chosen, since their construction time obviously is in the order of 1 year.

PV plant	Symbol	Value
Size of unit (Net power output)		750 MW
Construction period	j	1 year
Energy requirement during construction	I	2.15 TWh
Energy production per year	E	0.975 TWh/yr
Scenario timeline	m	25 years

Table 9-56: Assumed energy figures for PV plant for energy payback calculation

The production of the PV plants itself requires less than three month including the production of the raw materials. The construction period indicated in Table 9-56 (1 year) includes the construction of photovoltaic manufacturing plants which have to be added during growth of the production capacity. With the data of Table 9-56 the following results are achieved (Table 9-57):

Results PV	Symbol	Value
Maximum growth rate	q_{max}	45%
Optimum growth rate	q_{opt}	40%
Installed capacity after 25 years (q_{opt})		3.4 TW

Table 9-57: Optimum PV growth rate for various energy payback times

Though photovoltaics has a somewhat worse energy pay back ratio as SOT and SPS, it is still short enough to allow for an installation of more than 3.4 GW over the next 25 years.

In Figure 9-21 a positive energy balance during the scenario period is only achieved if the annual growth rate remains below 45 %. By far the largest gain is achieved at an optimal growth rate of 40 %. However, these figures strongly depend on the annual energy investment (which in turn depends on the construction time). For instance, if the time for the construction of a PV plant including the construction of a PV manufacturing plant were assumed to be 1.5 years, the maximum and optimum growth rates are strongly reduced to 41% and 36 %, respectively.

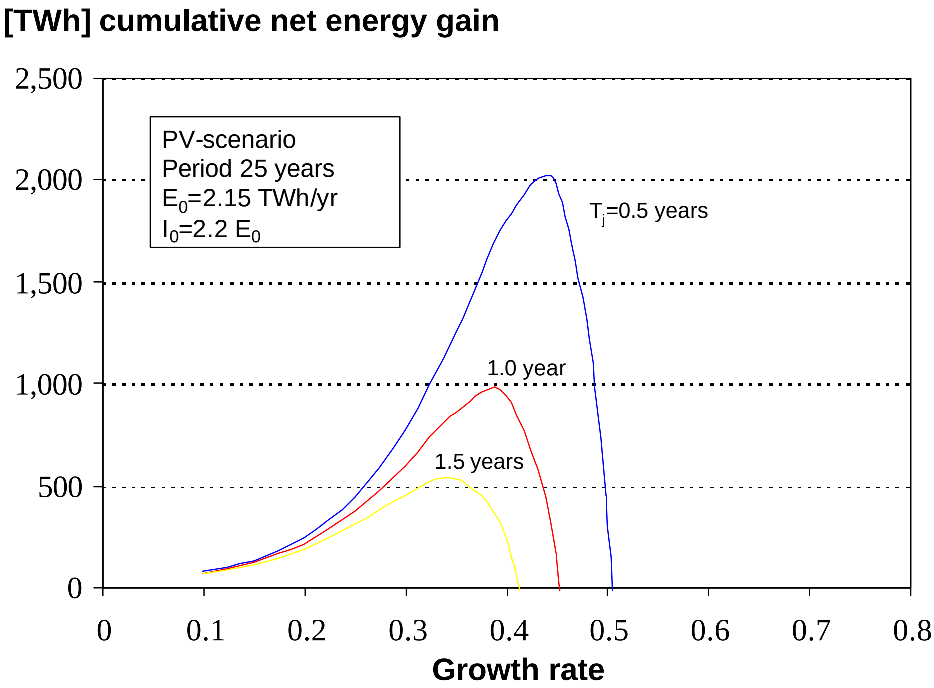

Figure 9-21: Cumulative net energy gain over 25 years time period within a PV-growth scenario in dependence of the annual growth rate. The construction time of the individual units is changed between 0.5 years and 1.5 years.

Apart from the cumulative energy balance over the full scenario period, the energy balance of the final year might be of interest. In Figure 9-22, this is detailed even further for the scenarios with an assumed construction time of one year for a single industrial scale production line.

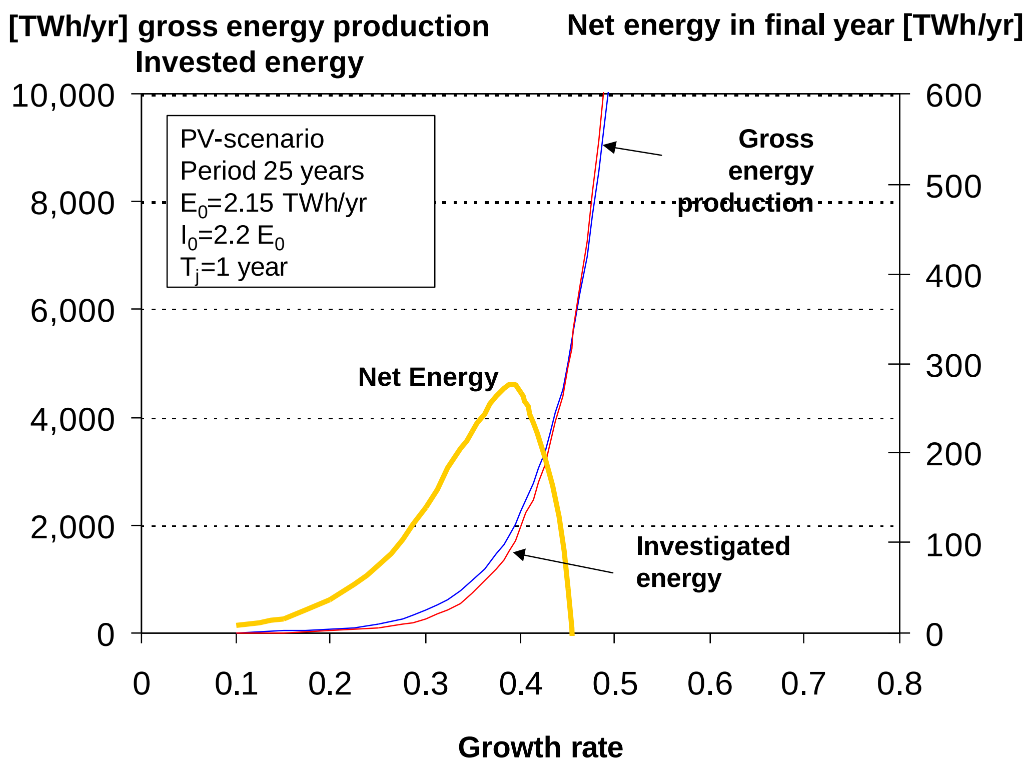

Figure 9-22: Annual energy balance for the final 25th year of the scenarios, exhibiting the net energy production as difference between the gross energy production (blue line) and the energy investment for power plants which are still under construction (red line).

Finally, Figure 9-23 details the annual energy balance over the full scenario time frame for a growth scenario with the optimum growth rate of 40 % per year. Gross energy production, energy investment and net energy production for the final 25th year are the same as in Figure 9-22 at a growth rate of 40 %.

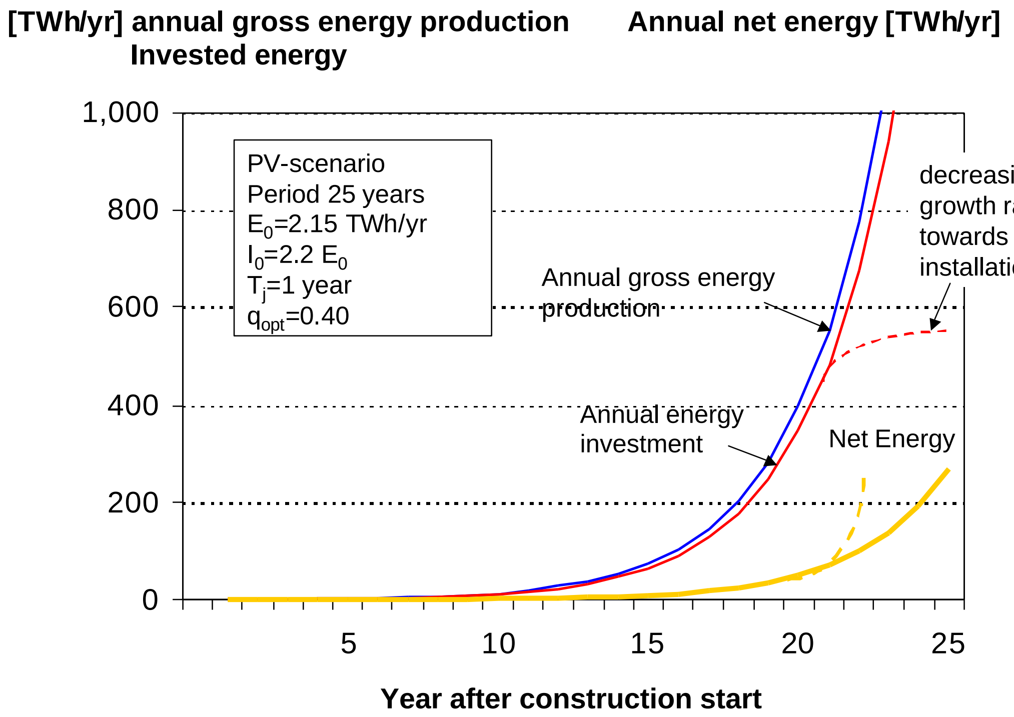

Figure 9-23: Annual energy balance of the PV growth scenario at annual growth rate of 40 %. Shown is the annual energy consumption for power plants still under construction (red line) and the energy output of already connected power plants (blue). The thick yellow line gives the annual net energy gain as difference of these two lines. The broken lines sketch the increasing net energy balance as soon as the capacity flattens according to the logistic model towards a constant value

With the help of the above derived formulae fast surveys on energy balances may be achieved to check various growth scenarios, and to test if a set power target for the final year x may be achieved with a positive energy balance over the scenario period.

A realistic growth scenario, of course, follows a bell shaped growth factor instead of constant growth as assumed here. However, the first half of the growth might be simulated with an exponential growth scenario to check its feasibility. As soon as the growth rate decelerates, the net energy balance is assured anyhow, as the completion of new power plants starts to rise faster than the energy investment for further power stations which are still under construction. This flattening of the capacity is sketched in Figure 9-23 by the broken lines.

9.4.3 Conclusions from net energy balance considerations

Under the assumption of a 2 year construction period per space-based solar power plant, a positive energy balance during the scenario period is only achieved if the annual growth rate remains below 73 %. By far the largest gain is achieved at an optimal growth rate of 66 %. After 25 years the total installed capacity would approach 900 TW starting with the 1 GW initial installation still having a positive net energy balance over the period of strongest growth. This indicates that a 500 GW scenario would not be restricted by energy investment constraints during construction. But we should keep in mind that the present worldwide photovoltaics production capacity is 750 MW per year. Thus to receive an order of about 1 GW surplus production capacity available for space applications would surely stress the producers ability for delivery unrealistically. This is not taken into account for in this analysis.

Regarding solar thermal power plants with hydrogen storage facilities and a construction period of 1 year, positive energy balance during the scenario period is only achieved if the annual growth rate remains below 60 %. By far the largest gain is achieved at an optimal growth rate of 54 %. After 25 years the total installed capacity would exceed 13 TW starting with the 108 MW initial installation - a figure well above the scenario requirements. From these considerations it can be concluded that no energetic restrictions limit the investigated scenarios.

9.5 Heat balance considerations

Though not within the scope of this study, some considerations concerning the influence of terrestrial and space-based solar power systems' impacts on the earth's heat balance are discussed in this chapter. A common consortium viewpoint concerning relevance and scientific foundation of this topic could not be established. The scientific understanding of this issue is "very low" [IPCC 2001] and the concept of 'Thermal Burden Multiplier' is not prevalent in atmospheric sciences. The two viewpoints within the consortium thus are documented alongside.

9.5.1 Space solar power systems

a) History of the concept

An inescapable perturbing factor -- though repeatedly rejected by conventional analysts -- is the thermal burden that is associated with any power generation method (i.e. using fossil fuels, nuclear reactors, photovoltaics, hydro, ...). Many authors (including [Fritsch 1991] have fallen in the trap to consider the environmental impact of power generating systems from a merely global thermal perspective, reasoning that to reject 0.1% more power a body like Earth needs only to increase its average temperature by 0.1°C. That average temperatures, however, do not mean too much, is demonstrated by the role that the vegetation cover does play in modulating weather phenomena [Rasool 1994]: these may appear tiny on a global scale, but can be extremely significant on a biospheric, and major on a human scale.

It seems, however, that very few previous studies have addressed the two issues – i.e. energy ratio and thermal burden - in combination, which might explain in part why the energy-ratio studies did not find it opportune to distinguish between energy expenditures within the biosphere and those occurring outside it. Such a categorization is, however, central to a correct treatment of the thermal burden issue.

The concept of "thermal burden" was introduced by [Ehricke 1971], who quoted a value for the energy flux absorbed by the terrestrial vegetation equivalent to 0.51% of the total heliogenic flux entering Earth. Thus, the 0.1% heat-flux equivalent mentioned above raises to correspond to almost 20% of the value for the terrestrial vegetation, clearly a more alarming fraction. [Criswell 1984] discussed the carbon-equivalent processed for power-generation purposes, observed that it does approach the carbon flux through the biosphere, but did not press the point otherwise in terms of the associated thermal burden.

It remained apparently to [O'Neill 1992] to first point out that the actual burden strongly depends on the technology used for the plants: "[Rectennae] convert [microwaves] with an efficiency so high that less than 100 W of waste heat goes into the environment for every 1,000 W that goes into power lines. For coal or nuclear the numbers are: 1,500 W waste or 2,500 W total; for ground-based solar they are several thousand watts waste plus another thousand to make up the total - different from an Earth without solar cells - because solar cells absorb more heat than the ground they cover" [O'Neill 1992].

[Strickland 1998] built of this insight, collating albedo data for different grounds, and assessing the waste heat released by rectenna and PV plants.

We define the thermal burden as the (total) additional power (i.e., averaged energy released per unit time) released into the biosphere in conjunction with human (industrial) power-generation processes [Bernasconi 1994]; it results from the sum of three terms:

- all (including the useful part) the primary energy freed for power-generation purposes
- the differential solar energy amount absorbed as a consequence of the local change in albedo (reflectance) induced by the presence of the power plant
- the total energy investment needed to implement and operate the power plant, and to process its fuel (in whichever form).

For ease of comparison purposes, we use a thermal-burden multiplier, M, the ratio of heat energy released into the biosphere for a unit of usable energy. A previous analysis of existing and proposed power generation systems [Bernasconi 1994] showed that we are confronted with three primary classes of methods:

– thermal systems, with moderate energy payback times and negligible albedo impact,

– ground solar systems, with long energy payback times and large albedo impact,

– hydro and space power systems, with very short payback times and negligible albedo impact.

b) Space option

The results of the energy analysis presented in the preceding Section need but a few additions to allow the computation of the thermal burden multiplier (Table 9-58). The three factors that contribute to the energy burden are expressed as average power (TJ/a). The primary energy released results from consideration of the total microwave power that enters the atmosphere, while the energy investment is the average yearly fraction of the total energy investment.

To estimate the solar albedo change, we began by assessing the fraction of the rectenna's land surface that would be covered by the dipole aerials, reflecting meshes, and support members, or about 11% with the geometry used to estimate the rectenna mass requirements. The solar absorptance of these members was taken as 0.3, a value near to that of common white paints, as well as blank metal surfaces. For the undisturbed surface, we looked at the impact on desert area (solar absorptance, 0.75) and on grassland (0.8); the average insolation we varied from 250 W/m² (maximum scale value on the plots used in WP-1; North-African regions), down to 210 W/m² (well-exposed area in the "European Sun-belt"), and to 125 W/m² (continental Europe North of 45°). The altered albedo was computed by the rule of mixture, and led to negative power contributions (i.e. less solar energy retained at the soil level in presence of the rectenna) in all cases. These contributions varied from -12.38 to -6.88 W/m² – after excluding the extremes, like grassland in North-Africa. For computing the thermal burden multiplier, the case grassland/Sun belt was used, being an intermediate value. As Table 9-58 shows, the albedo change roughly compensates for the operations energy investment.

As expected, the thermal burden multiplier is quite small for all SPS cases, being mainly determined by the efficiency of the passage of the microwave beam through the atmosphere (Table 9-58 and Table 9-59). The difference between the two model approaches for the main scenarios seems clearly smaller than the expected accuracy of an energy analysis exercise.

Plant Type		250 MW	1 GW	5 GW	10 GW
Total energy investment E_{inv}	TJ	9145	33510	168142	342138
Energy output per year	TJ/a	1971	31315	156576	312206
Primary released energy per year	TJ/a	2937	46660	233299	465188
Average energy investment per year	TJ/a	305	1117	5605	11405
Solar power due to albedo change	TJ/a	-1067	-3591	-17961	-36745
Thermal burden energy	TJ/a	2174	44185	220943	439848
Thermal burden multiplier		1.10	1.41	1.41	1.41

Table 9-58: Computation of the thermal burden multiplier – Terrestrial-analogue model.

Plant Type		250 MW	1 GW	5 GW	10 GW
Total energy investment E_{inv}	TJ	31049	81529	236237	479267
Energy output per year	TJ/a	1971	31315	156576	312206
Primary released energy per year	TJ/a	2937	46660	233299	465188
Average energy investment per year	TJ/a	1035	2718	7875	15976
Solar power due to albedo change	TJ/a	-1067	-3591	-17961	-36745
Thermal burden energy	TJ/a	2905	45786	223212	444419
Thermal burden multiplier		1.47	1.46	1.43	1.42

Table 9-59: Computation of the thermal burden multiplier – Hybrid model.

9.5.2 Photovoltaic and solar thermal power plants

The concept of the so-called thermal burden as discussed in [Bernasconi 1994] consists of three parameters:

1. thermal energy freed according to the primary fuel which is required for power plant operation
2. thermal energy freed according to the change in albedo
3. thermal energy freed according to the primary energy effort to erect and maintain the power plant and supply the fuel which is required for power plant operation

The freeing of energy from above listed sources is highly heterogeneous. It occurs at both different time scales and geographical distributions which thus results in completely different impact pathways. Consequently, above stated topics are further examined one by one for the sake of a transparent conclusion drawing. Otherwise, impacts from freed energy spanning over the whole life-cycle of power plants cannot be differentiated from each other.

The first topic of above stated list is examined in the following chapter a) "Heat release during operation". In subchapter b) "Change in albedo" the impacts due to changes in albedo are discussed. And finally, the third topic is calculated in chapter 9.2.

a) Heat release during operation

Heat which is released during the operational lifetime of power plants may have an impact to the biosphere if this energy would otherwise not be part of the ecological system. This topic rightly applies for power plants which rely on primary energy sources which otherwise would not be freed to the biosphere in the timeframe of power plant operation. This applies to power plants which are fuelled by fossil fuels (such as oil or gas), nuclear power and space based power plants. This topic applies only as far to the renewable energy technologies which are considered in this study – namely solar thermal and photovoltaics – as a change in albedo may occur (see following subchapter for a discussion on this topic). Terrestrial solar power system are driven by solar irradiation which would anyway enter the near ground biosphere. In contrary, space based power systems release additional energy to the biosphere as additional energy from space is brought into the system via both near ground microwave transmission and microwave conversion losses. It thus frees additional energy to earth and atmosphere. The system boundaries for this consideration are depicted in Figure 9-24.

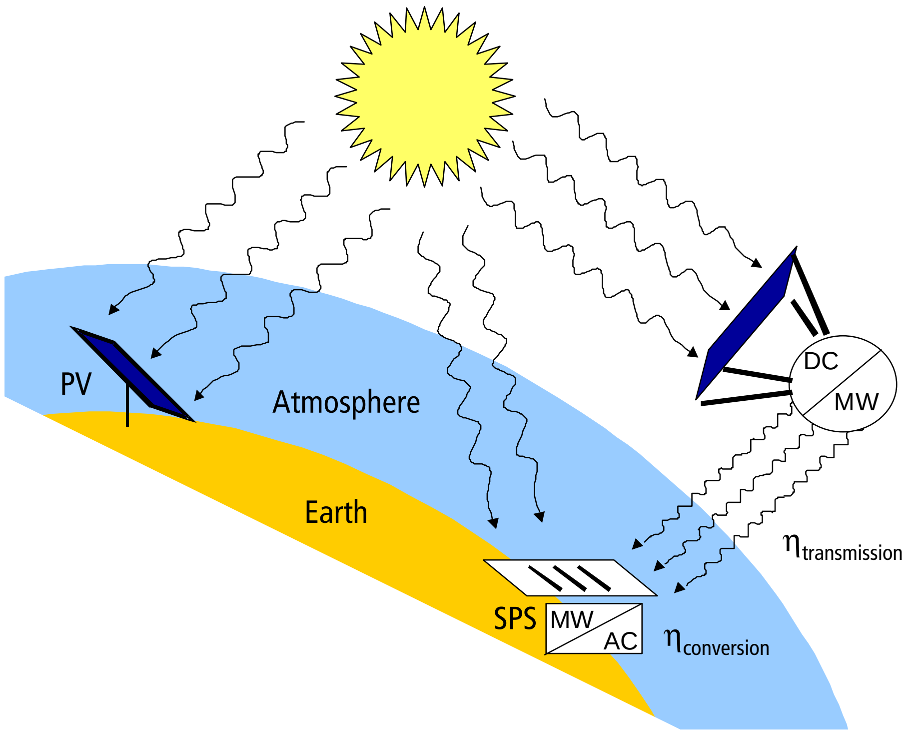

Figure 9-24: Schema of additional energy brought in the earth's ecosystem (left: PV with no additional heat release, right: additional energy input from SPS); further effects from change of energy balance may result from a change in albedo (see subchapter b))

However, changes in albedo may arise from PV and SOT installations. The degree of change and resulting impacts are further examined in the chapter b).

b) Change in albedo

The albedo coefficient represents the degree of solar irradiation which is reflected by any surface. Thus, different surfaces have different albedo coefficients which highly depend on the sun's elevation, i.e. its latitudinal position. The albedo coefficients is a function of the wavelength, too. Impacts resulting from a high/low reflectivity may be assumed globally (climate change) and locally (microclimate).

The scientific understanding of the albedo effect regarding climate change is currently very low. It is assumed to be significantly lower than that of a number of other radiative forcing shown Figure 9-25, such as the group of greenhouse gases, sulfate and possible indirect aerosol effects.

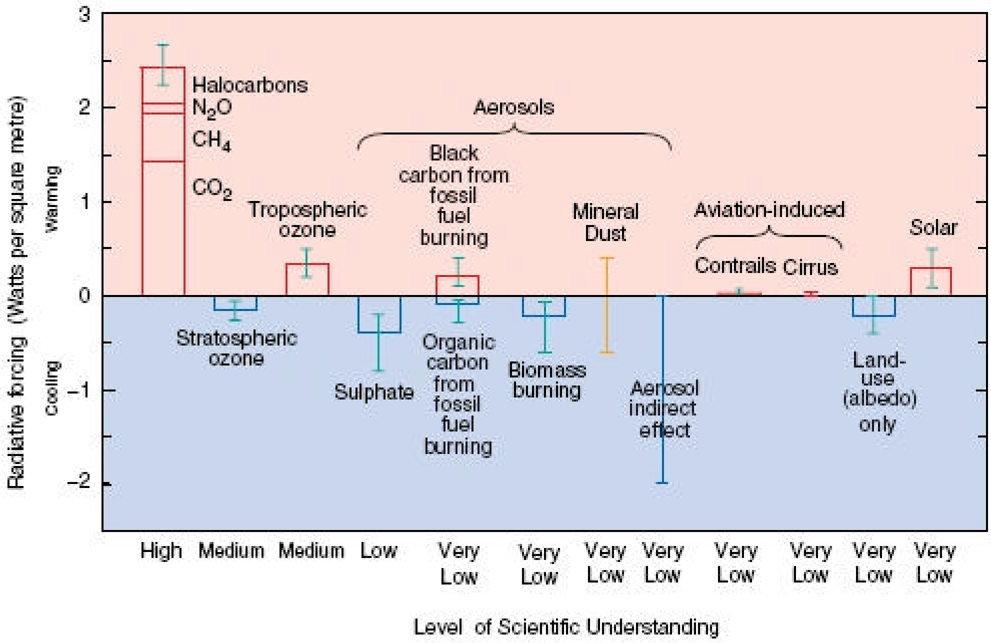

Figure 9-25: Global, annual-mean radiative forcing of the climate system for the year 2000 relative to pre-industrial era (reference year 1750) [IPCC 2001]

Typical albedo data for different earth surfaces are depicted in Table 9-60.

Type of surface	Albedo	Source
Water	0.05 .. 0.25	[Bernasconi 1994]
PV modules	0.15	[Bernasconi 1994]
PV modules	0.20	[Genchi 2002]
Grassland	0.20	MCBC
Crops and Soil (average)	0.25	[TNC 1996]
Desert soil	0.25	MCBC
Concrete roofing	0.27	[Bernasconi 1994]
Solar thermal	0.30	[Thomas 1991]
Concrete (uncolored)	0.35	[TNC 1996]
Sand (dry) "Nutzfläche trockener Sandboden"	0.38	[Thomas 1991]

Type of surface	Albedo	Source
Aluminum (polished)	0.71	[Bernasconi 1994]
Metal (polished)	0.90	[Bernasconi 1994]
Snow	0.72 .. 0.98	[TNC 1996]

Table 9-60: Comparison of surfaces' albedo coefficients

Regarding **photovoltaic** (PV) installations, [Genchi 2002] developed a numerical simulation model (see Figure 9-26) and calibrated it with real world measurements in order to determine the impact of large scale PV application to the so-called urban heat island (UHI) effect.

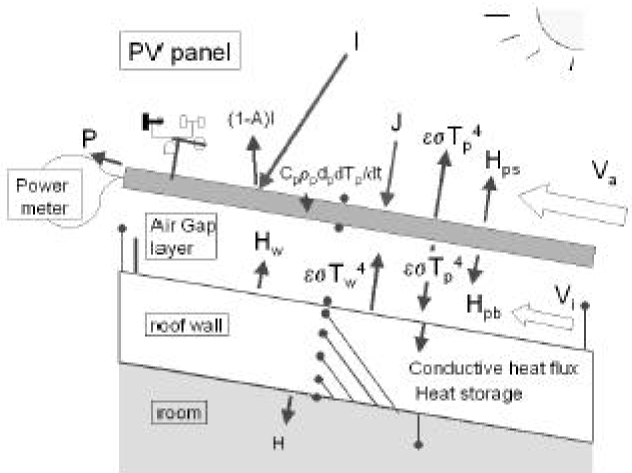

Figure 9-26: Parameter setup of a simulation model and measurements accomplished by [Genchi 2002]

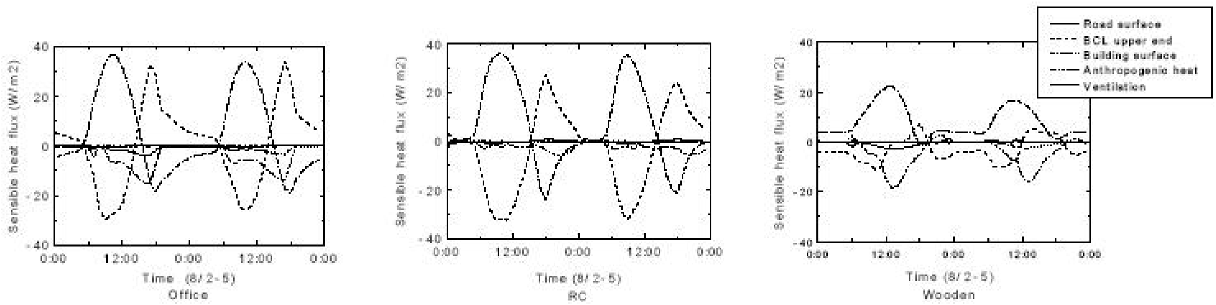

Figure 9-27: Differences in the heat balances for rooftops with and without PV installation for three different buildings which were examined (see [Genchi 2002] for details)

Without PV installations, the anthropogenic heat emission from three different types of buildings (office buildings, residential buildings made of reinforced concrete and wooden residential buildings) is ~400 W/m² in daytime on all building surfaces (facades and roof) in the study region Tokyo. The resulting sensible heat flux due to PV installations (roof coverage about 50%) resulted in an increase of heat flux between 20 and 40 W/m². [Genchi 2002] thus concludes that the resulting direct influence of PV installed on buildings to the urban heat island effect is negligible. However, he found that due to the PV shading the building's cooling effort was reduced by 2.7% at the office building and even by 10% at the wood residential building.

Aside the simulations and measurements conducted by [Genchi 2002], from a global perspective the overall relevance of PV installations is negligible, too: Even when considering the worst case (150 GW_e non-base load scenario with hydrogen storage, no facades-mounted PV modules, 0° tilt angle) the area which is occupied by PV is less than 4,200 km² compared to 17,118 km² for traffic purposes which are 2001 in place in Germany only, let alone approximately the same amount of space which is occupied by buildings in Germany in 2001 (Table 9-61 depicts current land use with albedo values equivalent to PV and SOT). However, glaciers are currently shrinking. If at all, PV plants may rather tend to compensate this loss of albedo on a global level.

Germany (2001)		
Area type	Area	Share
Water (lakes, rivers etc.)	8,085 km²	2.3 %
Traffic (so called 'Verkehrsfläche')	17,118 km²	4.8 %
Buildings and adjacent free space (so called 'Gebäude und Freifläche')	23,081 km²	6.5 %
Forest	105,314 km²	29.5 %

Table 9-61: Exemplary land use in Germany (total area 357,031 km²) in the year 2001 [Destatis 2003]

Regarding **solar thermal** (SOT) installations, [Thomas 1991] performed simulations and real world measurements concerning the SOT induced change of albedo. As reference albedo, he chose dry soil (0.38) which would be typical for regions with high levels of direct solar irradiation, i.e. regions where SOT plants would preferably be sited. Among other parameters, he logged the change of albedo for a typical sunny day with time. His record is plotted in Figure 9-28.

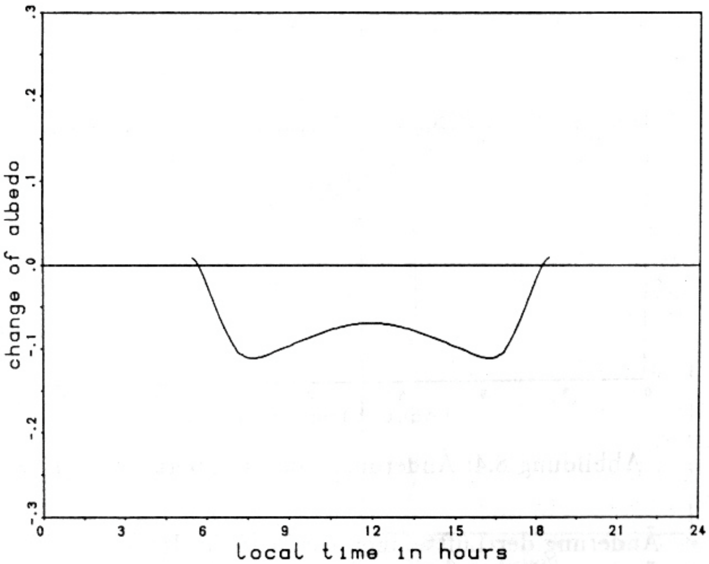

Figure 9-28: Change in albedo with time due to solar thermal installation on a typical sunny day at an reference albedo of 0.38 [Thomas 1991]

As can be seen from Figure 9-28, the albedo is reduced by an average of 8%-points. In the course of midday (which is most important for the system's energetics) the average decrease of albedo is 7.5%-points, resulting in an approximate decrease of reflected irradiation of 70 W/m² (short wave) and 50 W/m² (long wave). [Thomas 1991] concludes his study by stating that the resulting radiant balance, earth heat flux and sensible heat are well within the range of natural fluctuations, thus "the danger of unexpected effects appears to be low".

Regarding the change of **microclimate** due to PV module installations, the impact is comparable to the conversion of roofs to grassland. Concerning SOT plants [Thomas 1991] states that under humid conditions the possible induction of clouding may be a subject for further research. However, SOT plants are preferably sited on rather arid land for irradiation and space reason. SOT impact on microclimate is comparable to urban development (namely concrete) in arid zones.

Positive **side effects** may be drawn from PV and SOT installations. According to [Genchi 2002] the shading of buildings by PV modules decreases the cooling load of buildings by 2.7% - 10%. The shading of soil by SOT may allow a resettlement of vegetation in arid regions.

However, the overall impact is similar to other human activities, especially roads and buildings (concrete) as well as agriculture (grassland).

c) Conclusion

The change of albedo due to PV and SOT installations and its influence on microclimate are well within local natural variation. Compared to other human activities such as urban development or agriculture, the SOT/PV contribution to the change of albedo is minor (SOT) and even negligible (decentralized PV). Whereas the albedo of PV is comparable to grassland the albedo of SOT is comparable with concrete. However, the scientific knowledge on the local and global impacts of changes in albedo is low. This topic is thus subject to future findings.

Positive side effects may be gained from reduced cooling efforts for buildings due to PV installations and resettlement of vegetation in arid regions due to SOT installations. Additional heat is not released during the operation as fossil or ex-situ primary sources of energy are neither required by PV nor SOT plants.

10 RELIABILITY AND RISK DISCUSSION

The comparison of base load and non-base load scenarios presented in the previous chapters was done with a focus on costs. Therefore terrestrial and space concepts were selected, system architectures described and evaluated for the most economic concepts for each scenario. This chapter discuss further aspects to be considered for a more overall evaluation of these systems and scenarios. Figure 10-1 shows three parameters to be evaluated and considered for a more complete comparison between space and terrestrial concepts. In the following subchapters the previous selected and discussed technologies and system architectures are further discussed regarding their system reliability and potential risks. Though, a discussion on reliability and risk is rather of a qualitative nature, these issues are to be taken as serious as quantitative (cost) figures.

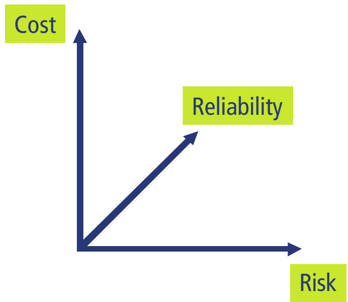

Figure 10-1: For an overall comparison between space and terrestrial power systems costs, reliability and risks have to be evaluated

It is the nature of this study that a comparison between terrestrial and space-based solar power systems is **significantly asymmetric** regarding data reliability and validity in all three dimensions. This is reflected in the following discussion of both systems, and in the conclusions. These are not recommendations as to whether commercial systems should be produced or not, but rather raises priorities for further research work.

Because the public perception of risk often tends to be rather subjective than objective, chapter 10.2 shall also help to create a higher transparency and understanding on particular subjects of large-scale application of solar power systems. Therefore, major issues attributed with terrestrial and space-based solar power systems are discussed as potential risks in order to give a whole picture and complement the scenario comparison which is based on cost assessments only.

Logically, any reliability and risk implication is eventually an economic risk.

10.1 Reliability

In this subchapter, the scientific concept and methods of reliability are introduced for a broader understanding of the differences between the concepts risk and reliability alike.

In the field of technology "reliability" deals with the issue "How often will a failure statistically occur in the course of normal operation?" whereas "failure" means an unscheduled behaviour out of the system's technical specification.

Reliability is usually time dependant, meaning that when a systems gets older reliability diminishes.

The various technologies applied have different failure rates.

Different system architectures lead to totally different failure paths.

A system architecture without backup systems is at most as reliable as its weakest link in the chain.

Relevant parameters to assess the reliability of a system are its failure frequency (mean time between failure – MTBF) and the mean time to repair (MTTR). Both parameters are cost relevant. MTTR costs are two-fold. They comprise the cost of repair and the loss of profit.

A trade-off between investment costs on one side and operation and maintenance costs (O&M) on the other side may generally be observed.

Methods to perform failure analysis are among others: Failure Mode and Effect Analysis (FMEA), Hazard Operability Studies (HAZOPS), Event Tree Analysis (ETA) and Fault Tree Analysis (FAT).

In general, the reliability of a system is raised by connecting two or more components in parallel. Regarding energy supply systems, this principle may be applied by installing additional components as backup systems, such as more satellites than actually required or an additional high voltage DC line. The reliability of a system can also be raised by splitting a single energy conversion unit into several smaller units. Thus, if one unit fails, only a fraction of the total energy supply is affected. This measure presumes, that the system complexity does not raise with the number of units applied. A higher system complexity generally results in a lower system reliability due to duplicating failure pathways.

The validity of component reliability figures highly depends on the practical experiences with the technology. Terrestrial solar power generation systems are up and running since more than two decades. As hardly any experiences could be gained by now regarding relevant technical parts of the space based solar power systems, a qualitative reliability assessment is the approach of choice in this study.

In a broader sense, "reliability" in the context of energy systems is equal to the idea of "security of energy supply" which is on top of the current political agenda in the USA and EU alike. This stems from mainly two reasons:

a) The dependence of the western industrialized countries from oil, gas and coal imports.

b) The large-scale attacks made on civilians in New York September 11 2001, Bali October 13 2002 and Madrid March 11 2004 represented a new dimension of violence and destruction threats from independent and worldwide operating groups. The weakest link – i.e. the action with the highest impact – is preferably selected by these groups and for general military operations alike. Infrastructure has always been the first target, such as energy, material, food and water supply (and, with increasing importance, communication facilities).

Generally, the use of locally produced renewable energy promotes the security of energy supply and thus has positively to be taken into account. Yet, if production is too centralized, the reliability of power supply is affected. Derived from [VDI 1994] we define that a single power installation of 10 GW electrical power capacity or more is critical regarding the overall stability of the European transmission grid.

In Figure 10-2 and Figure 10-3, the pathways of power generation are depicted according to the system architecture applied for scenario calculation. At this aggregation stage, it is not differentiated between PV and SOT. The major difference is the power size per generation unit which is higher with SOT. The pathways described represent the current state of system design as it is discussed in the scenarios of this study. Surely, it can't be exhaustive. However, modifications to make these pathways more robust will have to remain with possible future development stages.

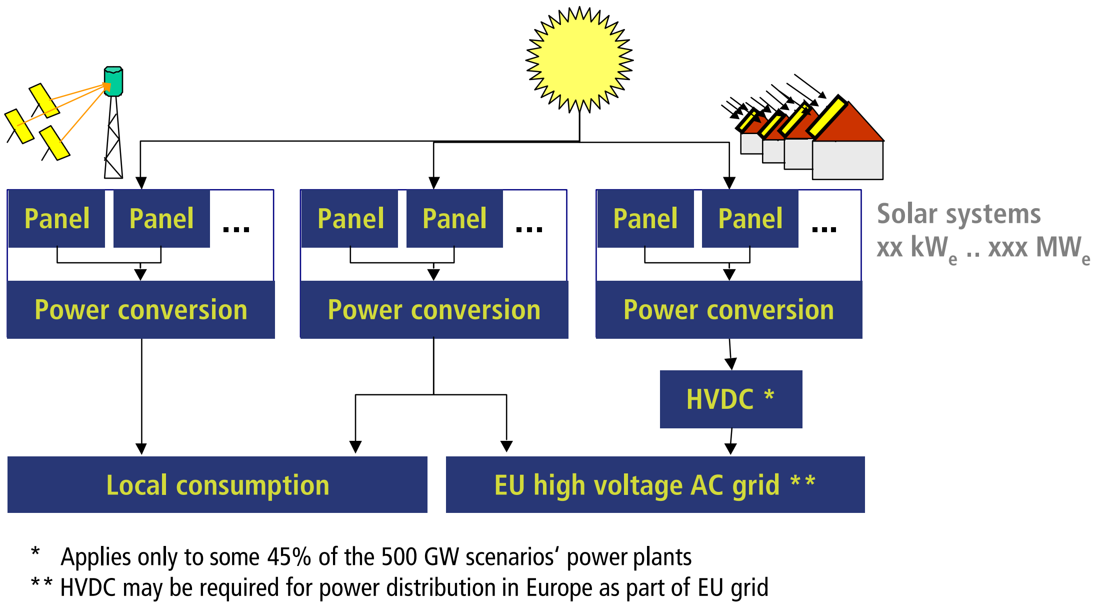

Figure 10-2: Pathway of terrestrial-based power generation

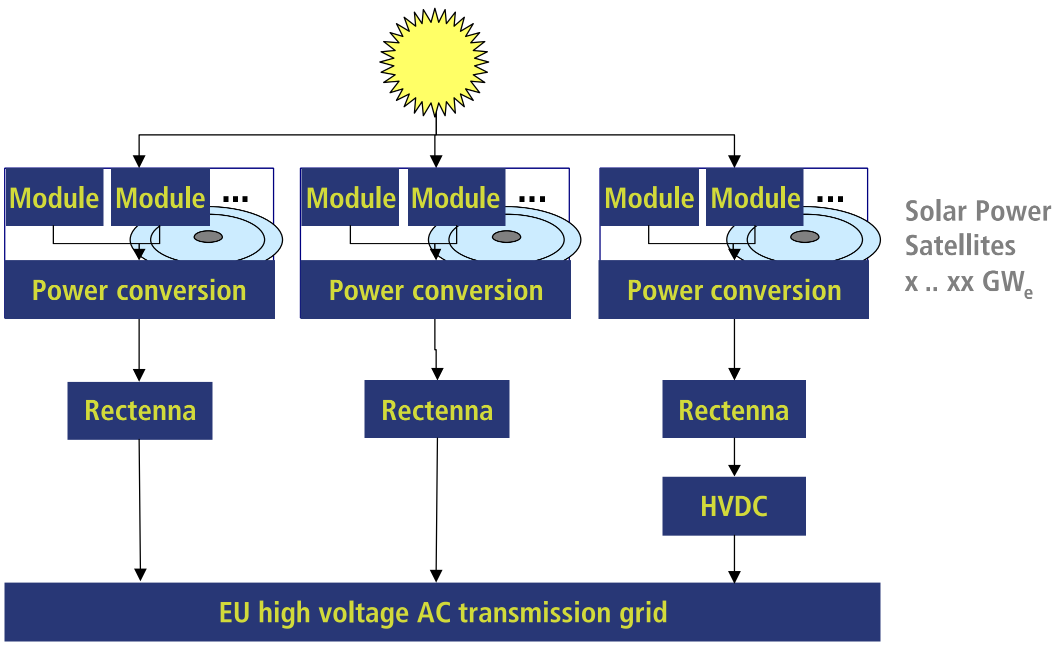

Figure 10-3: Pathway of space-based power generation

In Table 10-1 and Table 10-2, power generation pathways depicted in Figure 10-2 and Figure 10-3 are analyzed and their respective losses of power are calculated for the worst-case, i.e. the total failure of this path. Possible causes for power losses (no matter whether technology or human induced) are explicitly not discussed as there is always a n+1 failure constellation for everything, especially when considering such complex and large-scale systems. Full-scale FMEA (Failure Mode and Effects Analysis) and similar reliability analysis methods would have to be applied which is beyond the scope and timeframe of this study.

	Description	Worst-case consequence
1	One sun to deliver solar irradiation to n_{pan} solar panels (PV modules or SOT mirrors respectively)	Total loss of power output
2	At each of the n_{plants} power plants, n_{pan} panels feed their energy to one power conversion unit (inverter or gas turbine respectively)	Loss of power supply of one power plant ($1/n_{plants}$ of total power output)
3	At each of the n_{plants} power plants, electrical energy is fed into n_{lines} lines of the local distribution or European transmission grid respectively	Loss of power supply ranges from one power plant ($1/n_{plants}$ of total power output) down to one distribution or transmission line ($1/n_{plants}$*$1/n_{lines}$ of total power loss)
3a	For the 500 GW scenario only, HVDC lines are required for power transmission from North Africa to Europe and within Europe	Loss of one HVDC head station (x/n_{plants}*$1/n_{HVDC)}$ of total power loss)

Table 10-1: Principle terrestrial solar power system architecture and associated worst-case consequences for power generation

	Description	Worst-case consequence
1	One sun to deliver solar irradiation to n_{sat} solar power satellites with n_{PV} PV modules	Total loss of power output
2	n_{PV} PV modules per satellite feed power to one main power bus	Loss of power supply of one satellite ($1/n_{sat}$ of total power output)
3	Each satellites power is converted for microwave transmission	Loss of power supply of one satellite ($1/n_{sat}$ of total power output), i.e. loss of power supply of one antenna in the case of the 500 GW system architecture.
4	The microwave beam of one satellite is directed to n_{rect} ground rectennae (or n_{relsat} space-based power relay satellites which are not part of scenario calculations)	Loss of power supply ranges from one satellite ($1/n_{sat}$ of total power output) down to loss of power supply from one rectenna ($1/n_{rect}$ of total power output)
5	At each rectenna, microwave energy is converted into electrical energy	Loss of power supply of one rectenna ($1/n_{rect}$ of total power output)
6	With the 500 GW base load scenario at least, electrical energy is converted for high voltage DC transmission in n_{HVDC} head stations	Loss of power supply of one HVDC system ($1/n_{HVDC}$ of total power output)

Table 10-2: Principle space-based solar power system architecture and associated worst-case consequences for power generation

What can be observed is that the total failure of a single terrestrial PV or SOT plant has almost no effect on the overall power supply.

In two links of the chain, the consequences of terrestrial and space-based solar power systems could be equally far reaching: shading of the primary energy source (e.g. through 'global dimming', meteorites, severe volcanic activity etc.) and high-voltage DC transmission (where applicable). It is in the nature of terrestrial solar power supply, that their supply reliability inherently depends on the availability of sunlight, i.e. the accuracy of weather forecasts. The probability of a complete power failure is practically zero due to the geographical distribution of terrestrial solar power plants.

10.2 Risks

The concept of 'risks' extends the concept of 'reliability' (see previous chapter 10.1). Risks comprise both the occurrence probability of an incident and its respective consequences.

The concept of risk thus tries to give an answer to the question "How often will a certain incident probably occur and what are the consequences?".

Several types of risks are commonly stated:

– Economic risks (e.g. power demand does not develop as projected, currency risk)

– Environmental risks (damage to the environment due to the manufacturing, installation, operation and decommissioning of the energy system, both accidentally and as a result of polluting emissions)

– Political risks (e.g. nationalization of private property, terror attack and legal aspects such as who is the owner of the space respectively who has the rights to harness space energy?)

– Social risks (e.g. technology is not accepted by the public)

– Technological risks (e.g. major development targets are not reached, such as efficiency, resource or cost targets or – worst-case – a basic technology turns out to be not feasible)

Risks may be system immanent; risks may stem from intended or unintended operation outside of the system's operating parameters; risks may be given depending on the consequences of terror attacks; and risks may arise from so-called higher forces depending on the systems' response.

In the framework of this pre-feasibility study qualitative statements are made to describe major risks and points of discussion with regard to the power system's architectures applied for scenario building throughout this report. In the following, focus is put on major potential risks which are perceived and discussed in the public awareness referring to terrestrial and space-based solar power systems respectively.

10.2.1 Safety

Safety issues are primarily a matter of threats to human health and environment.

a) Accidents during system built-up

For the installation of space based power systems an overall great number of space flights (compared to today) are required. For base load and non-base load scenarios respectively up to 19,000 launches using an advanced space transports vehicle with a payload capacity of 350 tons (as assumed for space concepts in chapter 9 'Energy payback times (WP4)') or even up to more than 600,000 space flights using launch vehicles with 11 tons of payload capacity as assumed in the Fresh Look Study [NASA 1997]. Highest impact from space accidents may be assumed during the launching phase. Each Neptune rocket is initially carrying a propellant mass equivalent to approximately 17 tons TNT. For the closer neighboring vicinity, this poses no risks – except for the space ground personnel – provided that safety distances to neighboring buildings are given as usually is. The critical moment is the period shortly after lift-off. An exploding space vehicle of the Neptune size certainly poses a risk. Careful selection of appropriate launching sites may ease this problem, providing the required availability of such sites in Europe. If going outside of Europe the question of security of energy supply arises.

Depending on the extend of automated construction of space based solar power systems risks are also given in particular regarding the exposure of space workers to ionizing radiation [OTA 1981].

b) Accidents during system operation

For scenario calculation, microwave was selected as the technology of choice for power transmission from space to earth. Very high potential safety risks are prevalent in the event of a failure in beam traction. Especially for systems which transmit large amounts of power via microwave to earth – like 5 or 10 GW solar power satellites – high safety impacts on the environment are possible as discussed below in chapter 10.2.2c). A discussion of potential technical safety measures are given in chapter 10.2.4. To reduce the impacts of such an accident caused by failure of the microwave beam a highly reliable emergency shut down of the power transmission via microwave must be proven and guaranteed for the SPS systems. Since the 1970ies, concepts such as the retro-directive control system have been discussed and tested on small scale.

10.2.2 Environment and health

a) Waste disposal

For the decommissioning of solar power plants no specific assumptions for costs as well as energy payback calculations are considered and excluded for both space and terrestrial based scenarios. In contrary to terrestrial based solar power technologies, for the chosen SPS concepts taken from [NASA 1997] the decommissioning / recycling procedure remains unclear and are not discussed in the Fresh Look study report.

As the launch parameter discussion for base load and non-base load scenarios has shown in chapter 7, space transportation is one of the major cost issues for space power systems. Compared to terrestrial based solar power plants, for systems installed in space orbits the decommissioning may be more complicated and could cause additional problems. The development of space recycling options was not considered yet would have to be in the scope of SPS development. Otherwise, there is the risk to rely on parallel space developments beyond the sphere of influence of SPS development.

On the one hand waste disposal in higher orbits may cause major safety problems and risks for other satellites or space craft vehicles as well as could promote resource constraints (loss of secondary resources). On the other hand a recycling of SPS systems in space requires additional space flights which cause additional costs and environmental impacts.

For example, [Hazelrigg 1980] assumes that material would not be brought back from GEO but states that it would be far more valuable when recycled in space or disposed to a higher 'disposal orbit'.

b) Environmental impacts due to change of heat balance

Aspects of potential environmental impacts on the earth heat balance are already discussed in the course of energy payback calculation in chapter 9.5. The development and installation of large-scale power plants, terrestrial as well as space-based, may cause environmental risks due to change of heat balance. For example [OTA 1981, p. 12] describes that tropospheric heating may cause minor weather modifications. More detailed analysis of space and terrestrial concepts are suggested yet depend on further findings in the field of climatology.

c) Impacts of microwave exposure

Due to the fact that very limited experiences are available on power transmission via microwave in general and no power transmission from space to earth as assumed for the SPS scenarios exist in particular, several potential risks may be given for vegetation, animals and human health. To gain satisfactory answers and results as well as to have the option to exclude those potential risks, a technology analysis with focus on the risk imposed by microwave radiation is seen critical. Such a detailed analysis was not in the scope of this study. It was thus not possible to discuss and evaluate these issues in a satisfactory way. However, the most relevant issues are briefly described only for the sake of completeness of this report. Public perception on this topic could be a serious hurdle if not appropriately dealt with.

There is no scientific doubt that high frequency electromagnetic fields (EMF) cause biological effects, i.e. physiological reaction of biological systems. A matter of on-going scientific effort is to determine the consequences of these effects.

According to [TAB 2003], 20,000 scientific publications (primary studies) have been published by now plus additional several hundred meta-reports. Nevertheless, the public, scientific community and decision makers perceives the current state of knowledge as unsatisfactory due to the sometimes contradictory scientific results and conclusions on this topic from the experts' side.

Generally, it is distinguished between thermal and so-called non-thermal effects of continuous and pulsed microwave radiation respectively. Compared to an equivalent rate of energy deposition from a continuous-wave and a pulsed microwave field, the latter seem to be generally more effective in producing biological response ([ICNIRP 1997], p 506). Yet, scientific evidence is low on this topic. Whereas scientific evidence is prevalent on thermal effects from microwave radiation, non-thermal effects are still in scientific discussion. At exposure levels below significant and measurable heating, the evidence of harmful biological effects is "ambiguous and unproven" according to [OET 1999].

Early 2004, [Sernelius 2004] presented a theoretical model representing the force interactions of two blood cells in blood. When exposed to microwave fields in the frequency range of typical cellular phones and radiation densities equal to in-room temperature thermal radiation, he found that the attractive inter-molecular force was enhanced by surprising 10 orders of magnitude. The magnitude of the effect can be subject to personal health condition. Possible health effects remain speculative at this research stage, yet may result in e.g. contraction of thin blood vessels and growth of precipitates in tissues and organs (such as eyes). Though the model applied represents a "crude" first estimation, further research on this topic is advised considering the magnitude of the effect.

More recently studies from scientific laboratories in (among others) North America and Europe reported biological effects in animals and animal tissue under relatively low microwave exposure conditions, such as certain changes in the immune system, neurological and behavioral effects as well as effects on DNA [OET 1999]. If at all, under which conditions these effects pose a health hazard remains unclear.

So far, the most decisive scientific parameter for the exposition to high frequency electromagnetic fields is the so-called SAR value (specific absorption rate).

Exposure of a resting human to electromagnetic fields (EMF) with SAR values between 1 and 4 W/kg results in an increase of body temperature of less than 1°C. Exposure to EMF producing SAR values greater than 4 W/kg – i.e. 1°C – can "overwhelm the thermoregulatory capacity of the body and produce harmful levels of tissue heating" ([ICNIRP 1997], p 507). These observations seem to apply to humans and animals alike. In the discussion on the consequences from EMF exposure in the course of mobile communication, experts suggest to keep the temperature rise below 0.1°C which would be a safety factor of 10 below today's scientific evidence. Scientific evidence on adverse effects from microwave exposure is given in Table 10-3.

Impact/Effect	**Method**	**S [W/m²] /SAR [W/kg]**	**Classification**				
			evidence	**consistent indications**	**strong indications**	**indications**	**weak indications**
Cancer							
Cancer, all	Epidemiology					■	
	Experiment, animal	0,5/				■	
Leukaemia	Epidemiology					■	
Lymph gland cancer	Epidemiology						■
	Experiment, animal	3/0,01				■	
Cerebral tumor	Epidemiology					■	
	Experiment, animal	0,01/					■
Lung cancer	Epidemiology						■
Breast cancer	Epidemiology, women						■
	Experiment, animal	10/0,3					■
Eye cancer	Epidemiology						■
Testicular cancer	Epidemiology					■	
Skin cancer	Experiment, animal	10/1,2					■
other types of cancer	Epidemiology						■
	Experiment, animal	/0,5					■
Central nervous system							
Neuroendocrine system	Experiment, animal	/0,6				■	
Blood-brain-barrier	Experiment, animal, cell	/1			■		
brain functions	Experiment, human	0,01/		■			
	Experiment, animal	1/		■			
Cognitive functions,	Experiment, human	/0,9		■			
(learning) behavior	Experiment, animal	/0,07		■			
Neuromuscular functions	Epidemiology, children						■
Immune system							
Lymphocyte	Experiment, cell	15/1,5				■	
Cardiovascular system							
Circulation diseases	Epidemiology						■
Variability of heartbeat frequency	Epidemiology						■
Blood count	Epidemiology						■
Hormone system							
Melatonin	Experiment, human	0,5/					■
	Experiment, animal	/0,6				■	
Stress hormones	Experiment, human	0,2/		■			
	Experiment, animal	/0,6		■			

Impact/Effect	Method	S [W/m²] /SAR [W/kg]	Classification: evidence	consistent indications	strong indications	indications	weak indications
Reproduction							
Infertility	Epidemiology					■	
	Experiment, animal	0,01/				■	
Teratogenicity	Epidemiology					■	
	Experiment, animal	/2,3					■
Genes							
Chromosome aberration,	Experiment, human	0,1/		■			
Micro cores	Experiment, animal	/0,05		■			
	Experiment, cell	/0,3		■			
DNA fractures	Experiment, animal	10/0,6		■			
	Experiment, cell	8/2,4		■			
DNA syntheses & repair	Experiment, cell	0,9/0,00015				■	
Genotoxic effects	Experiment, Mikroorganismen	10/					■
Cell-mediated processes							
Gene expression, transcription, translation	Experiment, animal	/0,3		■			
	Experiment, cell	0,9/0,0001		■			
Cell proliferation, conversion	Experiment, cell	/1			■		
Cell cycle	Experiment, cell	5/					■
Cell communication	Experiment, cell	1/0,001					■
Ca2+ homeostasis	Experiment, cell	/0,03		■			
Enzyme activity, ODC[16]	Experiment, cell	10/				■	
Enzyme activity, others	Experiment, cell	/0,05				■	

Table 10-3: Classification of scientific evidence concerning health implications and biological effects from high-frequency electromagnetic fields [Ecolog 2001] (LBST translation)

Based on the suggestions of the International Commission on Non-Ionizing Radiation Protection (50 W/m² for occupational exposure and 10 W/m² for public exposure regarding equivalent plane-wave power densities for frequencies between 2 and 300 GHz) ([ICNIRP 1997], p 511) the European Commission proposed common EU exposure limits to its member countries in 1999. These limits reflect a safety factor of fifty below the lowest level which was found to trigger acute thermal effects [TAB 2003]. Critics state, that this exposure limit does not reflect any additional safety factor considering possibly existing and yet to prove non-thermal effects of high frequency electromagnetic fields.

16 Ornithine Decarboxylase: Important enzyme for the biosynthesis of proteins.

Italy is the only European country which set forth in 1999 exposure limits other than the EC suggestion. For microwave frequencies in the range of 3 MHz up to 3 GHz, EMF exposure limits of 1 W/m^2 (in general) and 0.1 W/m^2 (maximum indoor exposition in buildings where people stay longer than 4 hours) were laid down [BMWA 2004]. Italy’s motivation for more stringent exposure limits than any of the other European countries based on the ground of the precautionary principle.

In principle, Switzerland adopted the ICNIRP/EC limits, too, with the exemption of so-called "places with sensitive utilization" where people tend to stay for a longer period of time. These are places such as living rooms, schools, hospitals or kindergartens. There, exposure limits are ten times below ICNIRP/EC suggestions (1 W/m^2). Analogue to Italy, Switzerland based its decision on the precautionary principle [BMWA 2004].

In the Former Soviet Union, exposure limits were set to 0.01 W/m^2 ([OTA 1988], p 259) which is a factor of 1,000 below the ICNIRP/EC proposition. Since then harmonization work is underway. Other Eastern European countries [Gajšek 2002] and China [Foster 2002] have exposure limits rather reflecting rigorous Russian standards. Figure 10-4 gives an overview over Eastern European countries' exposure standards.

Up to date no evidence of health implications and biological effects from high frequency electromagnetic fields have been found, as seen in Table 10-3.

"Behind these differences [in standards for exposure limits worldwide] are large differences in perception of science and health protection" [Foster 2002].

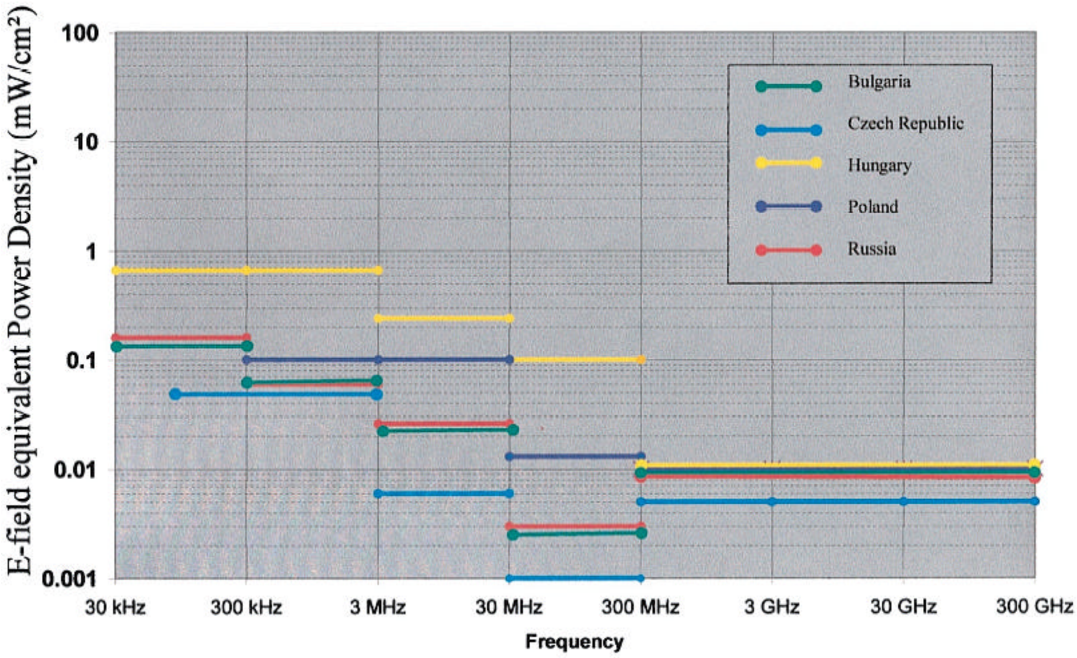

Figure 10-4: Limit values for unlimited public exposure in the frequency range 0.3–300 GHz for several East European countries (1 mW/cm² = 10 W/m²) [Gajšek 2002]

d) Reduction of terrestrial solar irradiation

- Global dimming

An economic risk for terrestrial based solar power systems could be what is publicly called 'global dimming'. [Stanhill 2001], [Roderick 2002], [Liebert 2002] reported the phenomenon of continuously reduced terrestrial solar irradiation by an average of 2-4%/decade since the 1950ies. As the power output of terrestrial solar power plants is directly linked with the solar irradiation, this would result in lower power productions. It is assumed that the phenomenon stems from an increasing cloud coverage and aerosol freight. Both are connected with air pollution and climate change effects. This phenomenon is scientifically still poorly understood. Further scientific verification is critical to estimate the degree of implication. In principle, an energy supply from a broad range of terrestrial and space-based renewable energies can ease this risk by mean of diversification.

- Cloud cover due to climate change

One of the expected effects of global warming is increased evaporation from the oceans. This in turn would have a range of effects, one of which may be increased cloud cover. Climate researchers currently do not have adequate data, either historical data on trends in cloud cover, nor accurate computer simulation models of what is a very complex atmospheric phenomenon influenced by many factors. Thus, for example, analysis of the potential effects of increased cloud cover has led different researchers to predict either accelerated warming due to a positive feedback mechanism, or decelerated warming through negative feedback. That is, the water vapour comprising clouds is itself a greenhouse gas which traps outgoing heat, but clouds also reflect incoming solar radiation, thus acting to offset solar warming. Hence the overall effects of increased cloud feedback mechanisms are difficult to estimate, and require better understanding of ocean-atmosphere coupling.

However, whether it increased or decreased global warming, increased cloud cover would have a direct effect on terrestrial solar energy production. Specifically, increased cloud cover would reduce the output per area of solar collectors in proportion to the reduction in intensity of sunlight at the Earth's surface, leading to the need to use larger areas of solar collectors for a particular power output. Increased cloud cover could also make terrestrial solar power systems less dependable as a power source, requiring proportionately larger areas of solar collectors and larger quantities of energy storage.

By contrast, increased cloud cover would in general have no effect on space-based solar power systems using microwave power transmission, since clouds are transparent to microwaves at the wavelengths being studied.

Although laser power transmission is not considered in this report, it may be noted that increased cloud cover could adversely affect space-based systems using laser power transmission, since laser light at many wavelengths is strongly absorbed by clouds.

The phenomenon of "global dimming" whereby the intensity of solar energy at the Earth's surface is measured to have been declining by a few percent/decade for the past few decades, is said to be due mainly to increased contrails from aircraft and increased air pollution. However, it may also be partly due to increased cloud cover.

e) Possible environmental impacts of effluents from space transportation

The release of water vapor at high altitudes and their possible impacts are discussed for space scenarios. As a result up to 3.6 million tons of H_2O would be released into the tropopause, the stratosphere and in the atmospheric layers above. This is significantly lower than the natural flow of water vapor from the troposphere (~1,210 million t per year) and with the water vapor release of today's aviation (~40 million t per year). Thus, this might be acceptable if the world-wide installed SPS capacity remained at 500 GW.

Further details as well as the discussion of NO_x emissions are given in Annex A6.

f) Pumped hydro storage

Pumped hydro storage was assumed as one storage option for terrestrial and space solar power scenarios. This technology is subject to topographical limitations. Huge land areas would be required to apply this technology especially with the 500 GW scenarios. Beside environmental aspects, public acceptance of very large-scale application of pumped hydro is likely. Large pumped hydro storage facilities are vulnerable towards military/sabotage actions.

10.2.3 Social

[OTA 1981, p. 10] describes the "discussion of SPS has been limited to a small number of public interest groups and professional societies. [...] Key issues that may enter into public thinking include environmental and health risks, land-use, military implications and costs. Centralization in the decision making process and in the ownership and control of SPS may also be important."

Risks, risk perception and public acceptance are usually different sides of the same coin. Even if assuming that all risks can be measured, risk perception and even more the public acceptance of risks generally tend to be a matter of personal experiences and values. Thus, any informed discussions about science and risks easily meet discussions about society and values [Duncan 2004] [Bouder 2004]. A discussion on risk perception and acceptance is beyond the scope of this study but has to be seen critical for a successful broad-scale introduction of any (especially large-scale / high impact) energy system.

A discussion of land-use issues are relevant for both space and terrestrial scenarios. There, two aspects seem to be mostly relevant. Firstly, the area requirement of plant facilities: Largely distributed, small-sized plants (such as PV) may acquire higher acceptance compared to large areas with restricted public access (such as SPS and SOT) even if the overall area requirements are larger. An overview over land area requirements is given in Table 10-4.

	SOT	PV (Si)	SPS
Size of single power unit - Hydrogen - Pumped hydro storage	 108 MW_e 153 MW_e	 1 kW_e – 1 MW_e 1 kW_e – 1 MW_e	 250 / 5,000 MW_e 250 / 5,000 MW_e
Area requirement for a single power unit - South Europe - North Africa	 22.5 km² 13.9 km²	 ~ 7 m² – 0.007 km² not applicable	 ~12 / 80 km² ~12 / 80 km²
Overall area requirement for scenarios [km²] - Base load (500 MW – 500 GW)	90 – 74,661 (113 – 117,495 incl. pumped hydro storage)	not applicable	25 – 8,000
- Non-base load (500 MW – 150 GW)	not applicable	0.05 – 4,200 (0.43 – 31,452 incl. pumped hydro storage)	25 – 8,000

Table 10-4: Land area requirements for the selected solar power technologies for various scenarios including hydrogen storage requirements (if not stated otherwise)

Secondly, the way this land is used. Microwave power transmission is likely to be accompanied by public concerns. Large-scale greenfield PV installations may also raise public concerns and ought to be strategically avoided as there is enough area which is not in competition to other utilization purposes. Regarding large-scale solar power plants in North Africa for the European power supply, a discussion on ethical aspects of power supply from so-called "Third World" countries should be led analogue to other African resource exports (iron, copper, platinum, diamonds, oil etc).

On the other hand social-political issues have a high relevance including geopolitical issues discussed in chapter 10.2.7. Another important issue for the SPS concept is the disposal of decisions for future generations due to the long lead time.

Furthermore, the needed for technology experts has to be discussed. SPS requires more specialized working groups ("Expertengesellschaft") compared to terrestrial PV and SOT technologies, which would allow wider public participation and understanding [Jochem 1988]. Centralized power generation tends to promote social monopoly structures.

In the event of a failure large systems create higher damages for the society in terms of blackout power. The failure of some SOT plants with 220 MW_e each (or even in the kilowatt range when considering decentralized PV plants) is less critical than solar power satellites with 5 or 10 GW_e per plant. Furthermore, international law for SPS systems requires the involvement of governments as discussed in chapter 10.2.6. E.g., in the event of a SPS accident the operator enterprise is likely to be liable only up to a certain amount. Eventual liability rests with the involved governments.

Due to the low scientific knowledge on the influence of changes in the local heat balance – which could result from side-by-side installation of multiple SOT plants or large PV fields in North Africa – there is a risk of compensations for changes of microclimate conditions if these are adverse (see discussion in chapter 9.5 'Heat balance considerations').

International legislation and coordination is also required for the deployment of intercontinental high-voltage DC transmission lines. This would also apply to offshore rectennae installations.

[OTA 1981, p 12] raises the question of public acceptance of possible adverse aesthetic effects on appearance of night sky due to satellites (up to 50 satellites in 500 GW scenario).

10.2.4 Technological

Technology assumptions for the selected space based solar power concepts are based on studies and technological predictions for 2030, particularly concerning power transmission via microwave and space transportation (SPS launching). Thus, potential technological risks are discussed in succeeding chapters.

- Development of power transmission via microwave for SPS

Data for terrestrial photovoltaic (PV) and solar thermal (SOT) power plants are based on existing systems which were extrapolated from historical learning curves. By now, microwave technology – as assumed for SPS scenario systems – cannot built on field experiences. No real-world demonstrator for high power transmission via microwaves from space to earth is available. This leads to technological risks given for the development and realization of space scenarios. Demonstration projects would ease this risk.

- Microwave beam positioning errors

  To reduce within to avoid negative impacts of a failure of the power transmission beam via microwave following technical solution is suggested for the SPS concepts: phase control of the microwave beam is maintained retro-directively by a pilot signal sent to the satellite from the rectenna as a pilot beam. Loss of the signal from the rectenna leads to de-phasing of the microwave beam, which is then spread over a 1,000 km diameter footprint, (average power density 1/10,000 of the level during power transmission). Beside the possible impacts which may occur for the environment due to such a technical measure which should be further investigated and discussed, ([OTA 1981], p 34) describes that a pilot beam from rectenna to SPS antenna "would take about 0.2 seconds to sense a position error and correct the pointing of the microwave beam...". As a possible result and impact "power variations of tens of megawatts from this source could make grid management extremely difficulty" (ditto). [...] "Buffer storage could be used to alleviate these difficulties". These would then have to be leveled via terrestrial energy storage facilities which were not part of scenario calculation so far.

- Microwave transmission and integration into electricity grid

  [OTA 1981, p. 34] describes that because "a microwave SPS is an electronic system, not a mechanical one, any power fluctuations due to beam pointing errors or to large-scale component failure would be rapid (the order of a second or less). The rest of the grid would only be able to respond relatively slowly (minutes), creating difficulties in controlling the frequency of current and overall power levels in the grid. The importance of this difficulty is directly dependent on the size of the SPS contribution. The smaller the output from a satellite-rectenna combination, the easier it will be to control."

- Fluctuation of power production of SPS systems due to changing earth-sun distance

  The annual variation in Sun-Earth distance is some 3%, leading to a variation in satellite output of about 7%. The change is so slow that it does not affect the satellite control. It is allowed for in the average figure for solar energy intensity. According to [Donalek 1978], "The effect on the utility system would be no different than it would be with conventional steam units which have reduced capacity in the summertime because of warm cooling water".

- Risks due to environmental conditions in space

  In contrary to what the laymen would suspect, the space is everything but 'empty'. Table 10-5 gives an overview over the challenging environmental conditions in space, possible impacts and required trade-offs with other design parameters.

Environment	Effect on array	Technical conflict	Orbit
Sun/eclipse cycle	Fatigue of interconnections	Long life array	LEO (GEO)
LEO plasma	Leakage/arcing	High voltage bus	LEO
Atomic oxygen	Erosion	Lightweight array	LEO
UV/Particles	Power degradation	High-efficiency array	GEO (LEO)
Residual atmosphere	Air drag	High power array	LEO
Micrometeorites	Short cut/arcing	High voltage bus	LEO/GEO
GEO substorms	Electrostatic discharge	Lightweight array	GEO

Table 10-5: Interactions of solar arrays in space under various environmental conditions [Bogus 1989]

Natural meteoroids are present throughout space. Additionally, man-made debris is mainly found in the lower earth orbit (LEO, <2000 km) and in the geo-stationary orbit ring (GEO, 36000 km). Whereas the natural meteoroid flux is dominated by particle sizes of some 5 microns to 500 microns, man-made space debris dominates the larger and smaller sizes.

Man-made space debris comprises a number of objects in space which may vary greatly in size [Ekstrand 2001]:

– Launch related objects (rocket-bodies, non-operational spacecraft, fragments from collision and explosions of upper stages/satellites

– Coolant release from nuclear reactors in space

– Surface degradation particles (paint flakes)

– Ejecta from former impacts

– Exhaust particles from solid rocket motor firings

"Any hypervelocity impact on spacecraft creates new space debris particles in the process" [Drolshagen 2001]. Space debris thus accumulates in orbit with time (snowball effect), though with a successive reduction in average particular size. The speed at which this process proceeds depends on the space utilization and the efforts which are undertaken to avoid the release of additional man-made space debris in the orbit and the efforts made to remove existing debris.

According to [Drolshagen 2001], the effects caused by a collision of spacecraft with natural meteoroids and man-made debris respectively are similar. In principle, the probability of such a collision is high and depends on the orbit altitude and attitude of the spacecraft. [Schäfer 2004] assumes some 10 to 100 hits per year and m^2 in LEO which have an impact on the surface. The numbers may be somewhat lower in MEO and much lower in GEO. The extend to which such collisions may affect the success of space missions largely depends on three parameters: size and velocity of the object which hits the spacecraft as well as type and arrangement of the spacecraft surfaces.

Only particles which are greater than a couple of centimeters can be traced from ground-based sensors [Ekstrand 2001]. In 2001 some 9,000 objects were reported by the US Space Command's Space Surveillance which are larger than 10 cm. It is estimated, that these represent ~5% of the number of particles in the centimeter size.

Small scale particles (micrometeorites, man-made space debris and successors thereof) resemble an abrasive atmosphere to solar arrays. Usually, direct hits of the solar arrays do not harm very much. The power output of PV modules in space decreases in a first assumption in relation to the affected module surface. "In special cases a conductive path and short circuit could be created" [Drolshagen 2001].

One failure scenario is assumed to be the cause for the loss of one satellite: When a particle hits the surface of a spacecraft, a plasma cloud evolves which covers for a few microseconds an area of up to several tens of centimeters around the center of impact [Droslhagen 2001]. In the best-case, this may result in electrical interferences. In the worst-case, if one of the power mains has already experienced a damage, the plasma can trigger a light-arc [Schäfer 2004] with severe consequences for the electric and electronic system.

Electrostatic discharges may even be triggered from relatively small particles in the sub-millimeter size as reported by [Drolshagen 2001]. These can affect the proper functioning of on-board electronic equipment. "The triggering of discharges on pre-charged spacecraft parts could well be the biggest risk from meteoroid and debris impacts in Earth orbit" ([Drolshagen 2001], p 538)

Extra risks to vehicles and facilities in space from meteor streams and storms are usually not very high compared to the relatively constant background flux of meteoroids and man-made debris [Drolshagen 2001].

Considering the large surfaces of space-based solar power satellites discussed throughout this study and the low knowledge about plasma generating impacts and their precursor conditions, further investigation on this topic is critical in order to ensure an overall economic viability of SPS. It is one of the major topics in the SPS 2000 study [Nagatomo 1994].

- Launch

  As discussed in chapter 7 launch is a major issue for the economy of SPS systems.

- Electromagnetic compatibility (EMC)

  The problem of electromagnetic interference comprises two basic aspects and can only be handled on a give and take basis: electromagnetic emission have to be kept below an agreed level as well as electr(on)ic appliances have to be designed to tolerate this very level of electromagnetic jamming by means of electromagnetic shielding and appropriate circuit design. Neither side can impose its requirements alone. Further research should thus examine potential electric interference with other space, air and ground-based applications, such as commercial satellites, air traffic, radar, radio etc.

10.2.5 Economic

In the event of stranded investments, economic damage from space-based is greater due to higher up-front investment efforts per power unit put into operation (the relevant parameter for comparison are the cost for the first power unit which are depicted in Table 10-7).

Other renewable energies – such as PV, SOT, wind, geothermal – proceed faster/ahead along the learning curve due to long lead times of space-based solar power system development and installation. This poses an economic risk to SPS operators as their market share may be lost at the time when the first system is put into operation.

Taking a brief look on the insurability of space-based solar power systems, how likely is it that SPS can be completely covered on a commercial insurance basis? It is a common code of practice in the insurance business not to insure risks that are uncertain. This can be observed e.g. in the cellular phone business since a couple of years [Reim 2004] where major insurance companies deny to cover operational risks of mobile phone equipment. This could be applicable to SPS, too, as similar uncertain risk pertain and the financial consequences could be great. Thus, it is very likely, that governmental bodies would have to cover the risks beyond a certain financial threshold as it is common practice in the nuclear industry (in Germany 2.5 billion EUR since 06.01.2004). This practice in the nuclear industry is under public discussion. See also chapter 10.2.6 concerning the principle liability of states for space activities.

Looking for example at very large-scale offshore wind parks with investment requirements in the order of 1-2 billion EUR, in several round table meetings the various players (turbine manufacturers, plant and grid operators, conservation associations, financiers, certifiers, regulatory bodies and insurance companies) were brought together in Germany to facilitate a dialogue. Risks could be averted by tackling potentials problems which prevail at the different parties. A similar process for SPS could make clear the expectations of the various stakeholders which are potentially involved in the development, deployment and operation of space-based solar power systems.

The use of land for power production purposes was assumed to be without charge as discussed in chapter 1.4. However, this seems only to be likely considering decentralized PV installations on roofs, facades and noise barriers. All other installations will face the risk of potentially significantly additional economic burdens from land costs. This is especially the case considering installations in the densely populated central Europe (zone 2) where land area requirements are likely to be in competition with other land use such as urban or agriculture development, conservation areas etc. Sea areas can be in competition with commercial and non-commercial activities such as sea routes, wind farms, maritime natural reserves etc.

The assumed cost for PV systems for 2030 is based on cost and efficiency targets for the production of solar-grade silicon. This is the most critical hurdle in the line of future PV development. On the other side, thick film silicon technology was applied for scenario calculation throughout this report. In case further break-throughs regarding mass production can be achieved in the field of thin film silicon, this risk would drop significantly or even not be applicable at all. The degree of risk reduction would depend on the thin film technology applied.

If thin film PV achieved further break-throughs in mass production, the launch cost targets for space-based solar power systems would become more stringent compared to those stated in this report.

In case of PV the burden of investment is shared among a large number of (private) investors. Considering the economic concept of diversification, this implies low economic risks for power plant investors.

10.2.6 National and international legislation

a) National

National legislation stipulates several regulations such as safety regulations for installations and maintenance, regulation for decommissioning and recycling; protection of vegetation, earth, animals and population. In particular for SPS systems which require a strong international involvement and cooperation of several nations – especially when considering a 150 GW or 500 GW scenario – different scopes and contents of national legislation may lead to regulatory frictions in the development process. For that reason international legislation should be established and implemented.

b) International

Independent from the organizational structure and kind of SPS operator(s) – international governmental organization (IGOs), international non-governmental organizations (NGOs), multinational enterprises or national enterprises – Article VI of the 1967 Outer Space Treaty stipulates that "state parties (governments) are internationally responsible for the national activities by non-governmental entities. According to Art. II of the Registration Convention, only one state (government) may register a space object to obtain the jurisdiction and control of SPS. However, analogues to ISS (International Space Station), member organizations for SPS can arrange the jurisdiction among themselves." [Charania 2001, p. 6] Governments are thus eventually liable and economic risks are socialized.

International law "requires allocation of satellite frequencies and geo-stationary positions by the International Telecommunication Union (ITU). If SPS were to interfere with global communications, this could be a major obstacle to gaining ITU approval" [OTA 1981, p 38].

[OTA 1981, p 38] further states that "Ownership and control of the geo-stationary orbit has not been completely resolved, and attempts by equatorial states to claim sovereignty over it could hamper development of any geo-stationary SPS". [Jochem 1988, pp 306-308] concludes that the applicable Article I of the 1967 'Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies' could not establish a sound legal basis as its interpretation is still controversial among the potential user of SPS and third-party states. Thus, sensitive legal fields are not yet sufficiently regulated and require further strong attention. Envisaged broad-scale civil utilization of space, such as SPS, could be a catalyst to bring forward the required level of legal certainty.

The discussion for a prioritized use of the geo-stationary trajectories for communication, weather, earth observation and environmental protection satellites must be further considered and could hamper the realization of SPS scenarios.

Arms control in outer space is seen as a critical issue and potential problem for any broad-scale space utilitzation. Since the mid 1990ies, the 'Conference on Disarmament'[17] and

[17] Conference on Disarmament, Geneva: Member: France, United Kingdom, Russia, USA and China [TAB 2003a, pp. 131]

the 'Ad-hoc-committee for the Prevention of an Arms Race in Outer Space'[18] are blocked due to disagreements between major member states. Especially U.S. plans for the installation of a space-based missile defense system aggravated the deadlock situation in the promotion of an international regulatory for arms control. Furthermore an arms control in outer space is complicated due to the cancellation of the 1972 ABM-Treaty[19] by the USA in June 2002. The contract prohibits the development, test and positioning of missiles including system components in space.

The existing deficits of international space legislation and arms control in outer space are critical regarding the development of SPS systems as well as for any other civil utilization of space. Space activities even for civil purposes could – justified or unjustified – arise international opposition.

All in all, there is a certain but not negligible risk that the development of SPS is hindered due to deficits in the international legal framework.

Another issue is the question in which way future space 'debris' is regulated on an international level. If a polluter-pays-principle is set into force, additional economic risk may arise for SPS operators on how to deal with system components at the end of their operational life-time. An assessment of in-space recycling options were not part of this study and may cause an additional economic risk or would have to rely on space developments beyond the scope of SPS development, such as other economic utilization of space (e.g. space / moon based recycling).

10.2.7 Military and sabotage

In the following subchapters potential risks are discussed that may be given for solar power plant scenarios due to the military involvement and terrorist sabotage. These discussions are mostly applicable to any broad-scale development in space.

a) Vulnerability

"A full-scale SPS system would constitute a high-value target for enemy action. Whether an SPS would in fact be targeted in the event of hostilities will depend above all on how crucial it is to a country's electricity supply." [OTA 1981, p. 39]

[OTA 1981] describes that SPS systems could be attacked in a number of ways, e.g. by

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[18] PAROS - Prevention of an Arms Race in Outer Space: conferences from 1985 to 1994, since 1995 blocked. [TAB 2003a, pp. 131]

[19] ABM – Anti-Ballistic-Missile – Treaty between USA and Russia (former USSR), 1972 [TAB 2003a, pp. 136]

- ground-launched missiles carrying nuclear or conventional warheads
- orbiting anti-satellite platforms
- ground or space-based directed energy weapons
- strewing debris in the satellite's path
- interfering with or redirecting the SPS's energy transmission beam

In the following, relevant issues regarding military importance and terrorist sabotage are further depicted.

- Military

The 'Report of the Commission to Assess United States National Security Space Management and Organizations (Space Commission)', Washington D.C., 2001, summaries (on report pages 8 and 13):

"The relative depends of the U.S. on space makes its space systems potentially attractive targets. Many foreign nations and non-state entities are pursuing space-related activities. Those hostile to the U.S. possess or can acquire on the global market, the means to deny, disrupt or destroy U.S. space systems by attacking satellites in space, communications links to and from the ground or ground stations that command the satellites and process their data.

The ability to restrict or deny freedom of access to and operations in space is no longer limited to global military powers. Knowledge of space systems and the means to counter them is increasingly available on the international market. The reality is that there are many extant capabilities to deny, disrupt or physically destroy space systems and the ground facilities that use and control them. Examples includes denial and deception, interference with satellites systems, jamming satellites on orbit, use of micro satellites for hostile action and detonation of a nuclear weapon in space.

An attack on elements of U.S. space systems during a crisis or conflict should not be considered an improbable act. If the U.S. is to avoid a Space Pearl Harbor it needs to take seriously the possibility of an attack on U.S. space systems." [TAB 2003a, p 27].

[TAB 2003a] analyses that all states which possessed nuclear weapons had in principle the technological ability to damage satellites in several orbits by means of a high atmospheric nuclear explosion. Proliferation of ballistic rockets and nuclear weapons could raise this risk as well as the number of states and sub-national actors with nuclear capabilities.

Nations like USA and Russia have already the technological expertise to disturb satellites from ground-based or airborne locations. Other nations like China attempt to obtain these abilities as well. [TAB 2003a]

- Terrorist sabotage

The definitive worst-case scenario for space-based solar power systems could be the explosion of one of the space vehicles in the satellite orbit. High-velocity debris from the explosion may pose a threat for space-based solar power satellites, let alone the further commercial use of this and higher-altitude orbits. Thus, appropriate security measure would have to be developed and implemented.

A potentially weak-link for both terrestrial and space-based solar power systems is – though only required by the 500 GW scenarios – the high voltage DC (HVDC) transmission systems. For installations outside Europe (such as North Africa) this risk is certainly higher. Power density in HVDC head stations and transmission lines are the highest of all terrestrial parts of both systems. The higher the power density of an energy infrastructure component and the higher its overall throughput the more attractive it is as terrorist target. Large switch-gear facilities in the multi-GW scale for HVAC transmission thus are equally sensitive areas and are only required to connect rectennae to the high-voltage power transmission grid. They can easily be attacked by strewing electrical conductive stripes as has been done by the US air force in the Yugoslavian war. This would also apply to very large-scale offshore wind farms which are beyond the scope of this study.

Another potential target could be the launching pad during the start preparation phase of a Neptune rocket. As the number of launching pads and assembly buildings would be limited for this mission for cost and logistic reasons (see Table 10-6), potential economic consequences would thus be significant under adverse conditions.

Scenario size [GW]	0.5	5	150	500
Number of launching pads [–]	2	2	15	31
Number of assembly buildings [–]	1	1	8	16

Table 10-6: Number of SPS ground facilities for selected scenarios

The risk of potential terrorist attacks on critical ground and space-based facilities could be eased by appropriate system design (redundant system parts, reinforced housing, military defense installations etc.), yet at higher costs and system complexity as well as military/geo-political implications which are further discussed in the following subchapter. Generally, even if n possible failure paths are considered a n+1 attack pathway is likely to exist.

b) Military utilization of space

Space was always and first of all of military interest and only partially started to become also commercially interesting. Outer space offers high capabilities for military operations and high threat potentials against other nations. As 'area of responsibility' space is identified as a 'resource' which is highly vulnerable for civil applications in space due to animus foreign actors but offers also high potentials for military operations like the implementation of new military measures for protection, military deterrence, 'information superiority' and 'military superiority' in and through outer space. The 'Quadrennial Defense Review 2001' of the U.S. Department of Defense depicts the importance of space for the U.S. military: "Technological advances creates the potential that competitions will develop in space and cyber space. Space and information operations has become the backbone of networked, highly distributed commercial civilian and military capabilities. This opens up the possibility that space control – the exploitation of space and the denial of the use of space to adversaries – will become a key objective in future military competition."[TAB 2003a, p 26]

Some 170 military satellites operate in earth orbits. Numerous nations see in the potential growth of military operations and systems in outer space an increasing risk for the international stability. The majority of the UN members warn of an 'arms race in outer space'.

Space is a geo-politically sensitive subject. The United States of America clearly classified space as a national top priority. 'Space superiority' is seen as an important U.S. target as well as a key aspect for the transformation of the U.S. military forces. U.S. interests include the full integration of aerospace capabilities into the U.S. military to maintain 'space/information superiority'. As also described in the 'Transformation Study Report – Executive Summary, prepared for the U.S. Secretary of Defense, Washington D.C., April 2001: "Space capabilities are inherently global, unaffected by territorial boundaries or jurisdictional limitations; they provide direct access to all regions and, with our advanced technologies, give us a highly asymmetrical advantage over any potential adversary."[TAB 2003a, p 41].

In general, any large-scale space developments may evolve in two opposite pathways. The development of e.g. frequent and cheap access to space could 'civilize' outer space by allowing for many commercial applications, thus providing a higher transparency on space activities and creating economically powerful groups with an interest in preventing peace in space. On the other hand, the realization of a SPS scenario would require the improvement of existing technologies and the development of new technologies particularly for launching ('Space Support[20]'), space system installations in orbit (including systems for SPS maintenance such as micro-robotic satellites), new satellite concepts and microwave technology. These technological improvements would also offer direct and indirect options for an increase of military weapon forces. For policy and military new options for actions would be given.

The following potential capabilities of SPS systems need further consideration:

- jamming of civil and military communication [ICNIRP 1997]
- "detonation of electro-explosive devices (detonators)" ([ICNIRP 1997], p 515)
- "induction of fires and explosions resulting from ignition of flammable materials by sparks caused by induced fields, contact currents, or spark discharges" ([ICNIRP 1997], p 515)
- environmental warfare by means of weather conditioning [ICNIRP 1997]
- development of launch infrastructure for military purposes
- service robots or micro-satellites developed for SPS operation and maintenance could be modified for military use
- use of SPS infrastructure as basis for military facilities and operations or 'force multiplier' such as for communication or navigation for military purposes.
- development of microwave/laser technology for military purpose.

Since a blockade of the 'Conference on Disarmament' and the 'Ad-hoc-committee' for the 'Prevention of an Arms Race in Outer Space' in the mid 1990ies, no instrument for an arms control in space does exist today. Space-based solar power systems require a multinational 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.

Some of the recent and ongoing work towards a proposed new international treaty banning weapons in space are described in the following:

[20] 'Space Support' defined in the 'Strategic Master Plan for FY '02 and Beyond – Executive Summary', Air Force Space Command, 2000: capability and capacities for launching and positioning of hardware in space orbits as well as operation of space vehicles for military purposes. [TAB 2003a, pp. 38]

Continuing efforts over the past few years to achieve a new, unanimous, world-wide agreement banning the use of weapons in space centre on the draft document Prevention of an Arms Race in Outer Space (PAROS). A major starting point for this work was the presentation to the U.N. Conference on Disarmament in Geneva, on June 27, 2002, by representatives of the governments of Russia and China, of draft documents intended to lead to a new treaty.

These efforts both to reinforce the existing ban on space-based weapons of mass destruction and to form a new treaty, led by China and Russia and supported by a great number of countries, are described in [www.china-un.ch/eng/30622.html]. Recent steps include the adoption of resolution A/RES/58/36 by the U.N. General Assembly on December 8, 2003: "Prevention of an Arms Race in Outer Space" [Text at: http://ods-dds-ny.un.org/doc/UNDOC/GEN/N03/455/07/PDF/N0345507.pdf?OpenElement].

A more recent activity was a meeting on June 3, 2004, at which representatives of 18 countries supported the PAROS initiative. An interim goal of the ongoing activity is apparently to formally re-establish an ad-hoc Committee on PAROS in the U.N. Conference on Disarmament.

The subject of PAROS is due to be discussed again at the next session of the U.N. Conference on Disarmament from July 26 through September 10, 2004.

Supporting activities by the Canadian government in February 2004 are described in [www.cndyorks.gn.apc.org/yspace/articles/canada8.htm]. A notable point in the Canadian position is expressed as: "...putting weapons into space that could blast apart satellites will only make it more difficult for countries who want to use space for commercial purposes...".

Thus, the very limited scale of space-based commercial activities today makes weaponisation of space easier, due to lack of economically motivated opposition. Having large-scale business operations in space would create strong interest groups against weaponisation. Both China and Russia hope to reap economic benefits from their large investments in space technology development, and thus might have also economic reasons for initiating the PAROS activity.

10.3 Comparison of system characteristics

Table 10-7 gives a brief overview over some system characteristics.

	PV	SOT	SPS
Economic risk per single plant: 150 GW non-base load 500 GW base load	very low 0.0007 [3] – 10 [4] million EUR –	medium – 0.67 [1] - 0.73 [2] bEUR	very high 15.2 [5] bEUR 33.3 [6] bEUR
System vulnerability	very low (medium with large-scale storage and for large scale area installations like in North Africa)	low (medium with large-scale storage)	high
Single power loss	very low (< 1 MW_e)	medium (≤ 153 MW_e)	high (≤ 10 GW_e)
Technical hurdles	solar-grade silicon	none	launch (space transport), power transmission to earth
Development stage	operational / market phase in	operational / MW scale demonstrators	research / laboratory-scale demonstrators
Hurdles to economic viability	medium	medium	high - very high (above all launch costs)
Social acceptance risks	very low (medium for large-scale greenfield installations and in North Africa)	low - very low (medium for large-scale installations in non-aride areas and in North Africa)	high
Military risks	very low	very low	undecided (potential to 'civilize' outer space as well as potential to facilitate military utilization of space)

[1] Data for 220 MW_e SOT with pumped hydrogen storage (@ 1,000 GW_e installed capacity
[2] Data for 220 MW_e SOT with hydrogen storage (@ 700 GW_e installed capacity)
[3] Data for 1 kW_e PV system with pumped hydro storage (@ 2.2 GW_e installed capacity)
[4] Data for 1 MW_e PV system with hydrogen storage (@ 588 GW_e installed capacity)
[5] Data for 10 GW_e SPS system (@ 50 installed SPS systems = 500 GW)
[6] Data for 5 GW_e SPS system (@ 30 installed SPS systems installed capacity = 150 GW)

Table 10-7: Risk matrix

11 STUDY CONCLUSIONS

Terrestrial and space-based solar power supply systems are fundamentally different in a number of ways. They are to a considerable extent independent, due to geographical separation, and therefore largely not subject to the same risks. System unit sizes are significantly smaller with SOT compared to SPS and even more smaller with PV. Moreover, whereas terrestrial solar energy is most economical for supplying power at relatively low (PV) to medium/high load-factors (SOT), space-based solar power is better suited to supplying continuous power and power at high load-factors. As the respective technologies of the two systems improved, terrestrial solar power would become economical at higher load factors, and space-based power would become competitive at lower load factors.

In the following chapters the prerequisites and results of the study are summarized in a comprehensive form and discussed in a broader context. Finally, future fields of research are presented.

Data basis

The scenario calculations aim to provide specific energy costs for the comparison of various terrestrial and space-based technologies. However, due to the different technological maturity, data certainty varies to some extend:

– Space-based solar power system (SPS) calculations are predominantly based on NASA Freshlook Study [NASA 1997]. The three key elements for the space system are launch, photovoltaic system and power transmission. Neither of these elements have ever been built on an industrial scale. Due to very vulnerable availability of launch cost data the launch is considered as a parameter. For the energy payback – different from the Fresh Look study's assumptions – the Koelle's Neptune space vehicle concept was taken into account.

– Solar thermal (SOT) assumptions are based on 20 years of experience in operation and successive progresses in research. This experience is analyzed in various recent studies which are used for the preparation of this report.

– Photovoltaic (PV) calculations are based on almost 40 years of research experience. Learning curves are based on more than 20 years of industrial experience. Basic data are taken from various state-of-the-art publications combined with expert knowledge of the consortium members.

An error analysis was not in the scope of this study. Thus, a sensitivity analysis remains to validate the resilience of study results.

Power demand

Considering the potential electricity demand of EU-30 in 2030, 150 GW is the probable maximum supply share which might be gained by the power generation means discussed in this report for both base load and non-base load power supply schemes. A 500 GW base load scenario was considered in order to gain knowledge about cost degression and to give room for potential energy demands in energy sectors apart from direct consumption of electricity. Further energy demand could e.g. stem from the need of a sustainable transportation fuel, such as hydrogen produced via electrolysis.

Terrestrial scenarios

Solar thermal power plants are selected for base load scenarios due to highest load factors. All SOT plants can be sited in the 'European sunbelt' zone 1 apart from the largest base load scenario for 500 GW continuous power supply. There, 100 to 200 GW of SOT plants are installed in zone 0 'North Africa' depending on the storage technology applied. The 100 to 200 GW could have also been supply from decentralized PV installations in Europe. However, for scenario design and cost optimization reasons, the North African sites with a higher solar irradiation were chosen to complement the required power generation capacities.

PV plants – selected for non-base load scenarios – demonstrate the potential of cost reductions by up-scaling of production volumes. Furthermore, abundant potentials exist for their installation on roofs, facades, and other areas which are not under competition with alternative ways of area utilization.

For both scenario types the cost of storage make up a significant share of the overall costs. These cost results are based on isolated scenario considerations, i.e. not combining electricity produced by PV/SOT plants with other supply technologies such as wind, biomass, geothermal or hydropower. A mix of various renewable energies would allow the use of each technology's advantages. Therefore, the calculated costs, especially for PV, are worst-case cost considerations. Costs would be reduced by the cost share of the storage with other technologies if integrated into a more complex (and more realistic) energy supply chain.

Space based scenarios

Up to a scenario size of 50 GW, rectennae may be sited in the European sunbelt ('zone 1'). With scenario sizes of 100 GW and above the potential of land area for rectennae' siting in zone 1 is exceeded. Thus, rectennae also have to be sited in zone 2 'Rest of

Europe'. Potential off-shore installations are discussed but were not selected for the scenarios.

For SPS systems no operation and maintenance costs could be considered because data were not available. Also not included is the decommissioning of the space installed plants. These expenses would have to be added to the levelized electricity cost calculation (LEC) stated in this report. The influence of the electricity storage is marginal for the SPS scenarios as only considerably small storage capacities are required to cover the energy mismatch during the eclipse seasons.

For the largest SPS scenario of 500 GW around 6.7 million tons of payload must be transported into orbit. The Koelle space transportation vehicle with a projected capability to transport 350 tons of payload to LEO per flight was assumed for the calculation of launch costs and transportation related energy efforts. For comparison the US space shuttle has a transport capacity of 20 tons, the European Ariane 5 can transport up to 5 tons of payload to GEO. Considering the 500 GW base load scenario, carrying 350 tons per flight would require 19,000 flights over an assumed time horizon of at least 25 years (provided that transport capacities and launching pads are constructed fast enough). Even with the 5 GW-scenario about 175 flights are required with Koelle's space vehicle (some 1,000 flights with the US Space Shuttle and 12,200 flights with the European Ariane 5 respectively).

Electricity storage

Various means of energy storage are examined in this study. Two types of energy storage were selected for scenario calculation – pumped hydro storage and hydrogen production with subsequent re-electrification.

On one hand, concepts with hydrogen storage are less efficient and more expensive than concepts with pumped hydro storage if hydrogen re-electrification is considered only. On the other hand hydrogen storage shows several advantages against pumped hydro storage. It offers great potentials for cost reductions as well as further strategic synergies. Pumped hydro storage strongly depends on geographic conditions and requires considerable land areas for storage lakes. If only centralized pumped hydro storage plants were applicable due to geographic limitations, additional high voltage DC (HVDC) lines would be required.

On the other hand, hydrogen can be stored flexible due to the high modularity of hydrogen storage vessels. On-site energy storage via hydrogen reduces the need of HVDC lines. Off-shore rectennae may use surplus electricity to generate on-site hydrogen. In grid-connected applications, the re-electrification of hydrogen on a 'power-only' basis is usually not economically viable.

For stationary applications, such as household, commerce and industry, hydrogen is most efficiently utilized by means of combined heat and power (CHP) production. Yet, CHP was not in the scope of the study as only costs were assessed and no heat credits.

Hydrogen as transportation fuel could be another potential market. The hydrogen storage could be used for electricity/CHP production and transportation purposes at the same time. This would improve the utilization of hydrogen storage and thus improve the overall economic of a hydrogen storage system.

Comparison of base load / non-base load scenarios

Under the given scenario conditions, terrestrial solar power plants are most economic with pumped hydro storage at sites where this is available.

The cost of space transportation is excluded in SPS cost calculations due to the high uncertainty of future space transportation costs. The cost of space transportation is kept parametric for a separate launch cost reduction analysis. No dump credit was attributed with excess power in any scenario.

SPS systems for base load scenarios cannot compete with the combination of terrestrial solar power plants which comprise pumped hydro storage under the assumption scenario as listed in chapter 7.1. Yet, space systems eventually may be competitive to SOT plants with hydrogen storage for power levels larger than 50 GW.

Non-base load SPS systems may be competitive to SOT plants for power levels equal or larger than 100 GW (independent from the type of terrestrial storage facilities applied). Details on the resulting target launch costs of initially cost competitive SPS scenario are presented in the following subchapter.

Levelized energy costs (LEC) for SPS systems with rectennae installations in North Africa are lower compared to systems with off-shore rectennae siting; but more expensive than for SPS systems with rectennae installed on-shore in Europe.

Launch

Launch (i.e. space transportation) is the principal and most critical cost issue for SPS systems. The required learning curve targets are calculated for SPS launching in order to become competitive with terrestrial scenarios. Figure 11-1 and Figure 11-2 show the results for base load and non-base load scenarios.

Launch fuel costs which base on natural gas as primary energy source will not follow the learning curve for SPS launching but are forecast to increase until 2030. Thus, targeted launch learning curves for launch costs do not include fuel costs. Fuel costs are calculated with 64 EUR/kg$_{payload}$ based on a tripling of natural gas prices until 2030. However, this increase in energy costs is not included in the calculation of terrestrial and space based hardware costs. 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 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. However a change to new launch technology would shift to a different learning curve.

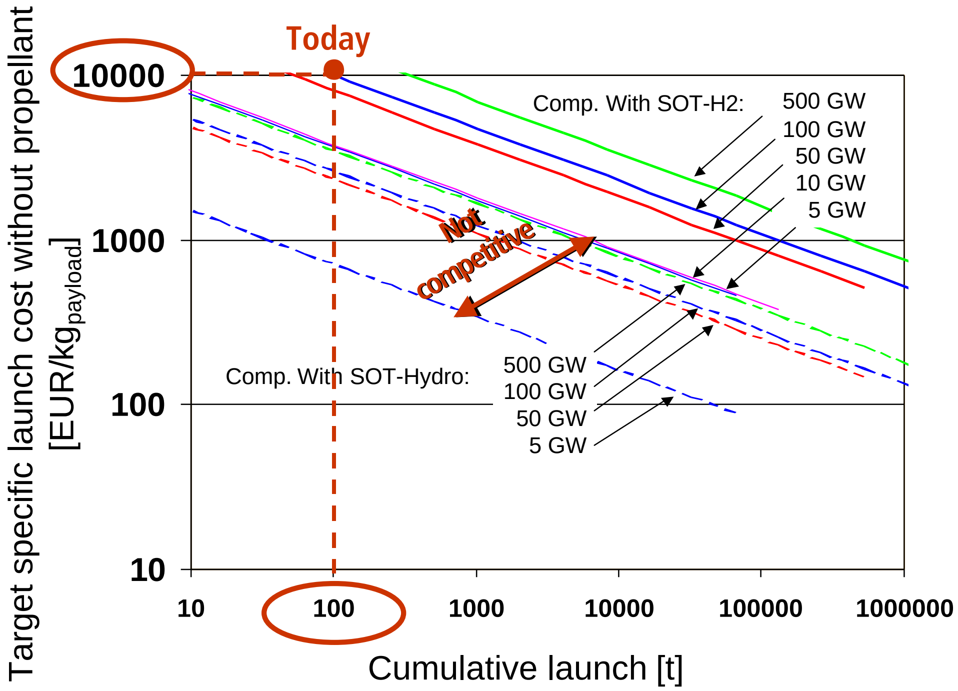

Figure 11-1: Calculated target learning curves for the launch cost (without propellant) in order to become cost competitive with the terrestrial <u>base load scenarios</u> based on pumped hydro storage and hydrogen storage respectively

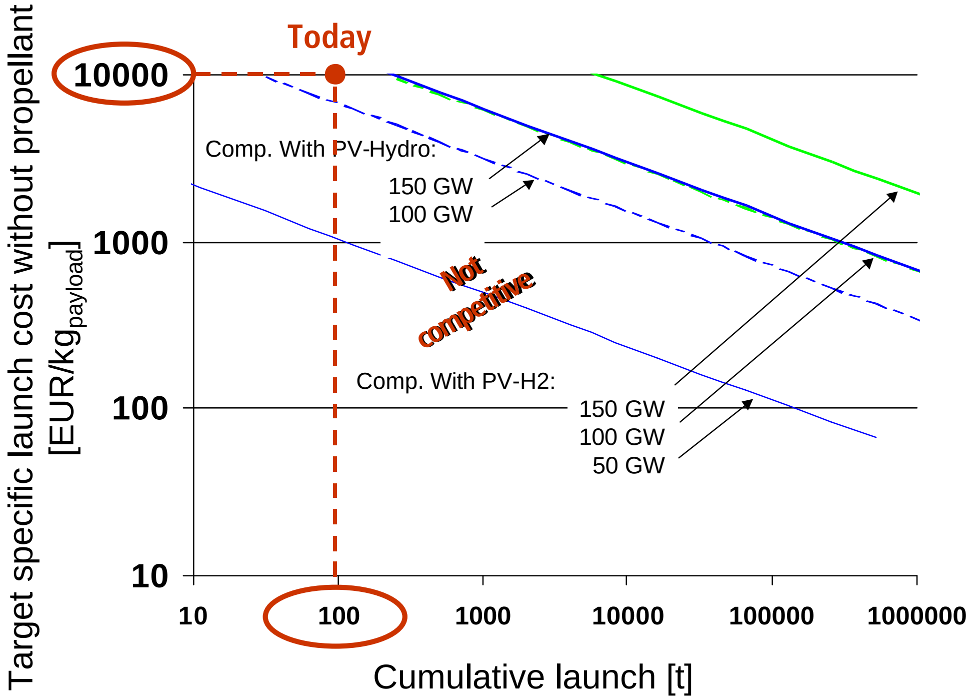

Figure 11-2: Calculated target learning curves for the launch cost (without propellant) in order to become cost competitive with the terrestrial <u>non-base load scenarios</u> based on pumped hydro storage and hydrogen storage respectively

For some of the scenarios in Figure 11-1 and Figure 11-2, the cost target requires final cost below some 400 $EUR/kg_{payload}$ (without propellant costs). In order to achieve such stringent cost targets within the given time horizon would require initial launch costs below 10,000 $EUR/kg_{payload}$ already today. These scenarios are thus not viable with an assumed progress ratio of 0.8. On the other hand, scenarios which allow for initial cost above 10,000 $EUR/kg_{payload}$ could eventually be economically viable in terms of achieving the final cost targets. Thus, focus should be put on learning curves for 100 / 500 GW scenario with H_2 storage (Figure 11-1) and learning curves 100 / 150 GW scenarios (Figure 11-2) as only these learning curves fulfill the initial requirements of initial launch costs of 10,000 $EUR/kg_{payload}$ at today's cumulated launch capacity of 100 t/yr. Further in-depth investigation is required here, especially in order to check the sensitivity of the results for the determination of critical parameters. It should also be noted that in these scenarios some 90% of the cumulated payload has to be launched at costs < 1,000 $EUR/kg_{payload}$.

This analysis is based on assumptions as listed in chapter 7.1 based on current technology, essentially expected launch vehicles. The use of new reusable launch vehicles can be expected to lead to lower launch costs.

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. 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 partial shading and possible electromagnetic interference. 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.

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.

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 calculated with the DIN (Deutsches Institut für Normung – German Institute for Standardization) methodology) 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 since the latter is undefined. 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. Calculations based on the main parameters indicate a lower resulting energy payback with using the Koelle vehicle compared to the NASA vehicle assumptions (see Figure 9-14).

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 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.

Reliability and risk

It is in the nature of this study that evidence on this issue is difficult for at least two inherent reasons: due to 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 given due to electromagnetic interference. 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 inherently 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.

With respect to the required up-front investment volumes for research and development, space based solar power is more similar to nuclear fusion than terrestrial solar energy. Space-based solar power and fusion technology are similar in some of their financial and operational characteristics. Both require high up-front investments and strong international cooperation, both could potentially provide electricity at high equivalent full load hours and both technologies are highly centralized in terms of installed power capacity per plant. In contrary to SPS, fusion by now has received substantial research and demonstration funding worldwide, though the probability to overcome major technological hurdles may be fairly higher with SPS.

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 km² 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 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 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 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.

Recent development of 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 in 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 competive to terrestrial scenarios.

Overall 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, especially for base-load scenar ios 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. 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.

Investment criteria

The European Investment Bank [EIB 2002] states – without claiming to be exhaustive – principal and widely recognized selection criteria which apply to individual projects but also programmes in the field of financing of power plants. In Table 11-1, these criteria are applied to the technological concepts investigated in the framework of this study on a qualitative basis (the deviant 250 MW Sun Tower concept which is only considered in the 0.5 GW scenarios is excluded from this discussion for reasons of non-competitiveness). Therein, the uncertainties in basic assumptions and reliability to meet development targets is not taken into account.

	PV	SOT	SPS
Quality and reliability of the primary energy source	high[1)] high[2)] low [3)]	high[1)] high[2)] medium[3)]	potentially very high
Compatibility with existing generation and transmission systems	medium - low[1)] high[2)] high - low[3)]	medium - low[1)] high[2)] high - medium[3)]	medium

	PV	SOT	SPS
Promising potential for demonstration effects and future developments	subject to assumptions		
Attractive lifecycle energy balance	'yes' to all technologies/scenarios (1.0 - 1.7 yr respectively 0.4 - 0.7 according to DIN)		
Environmental acceptability, including public participation in the decision-making process	medium - low 1) high 2) high 3)	low 1) high - medium 2) high - medium 3)	medium - low
Sound financial and economic returns, taking account of the external benefits of renewable energy whenever it makes sense	An analysis of the future electricity market is not in the scope of this study		

1) with pumped hydro storage
2) with hydrogen storage
3) without storage

Table 11-1: Investment criteria for energy systems including a qualitative evaluation

Considering Table 11-1, by means of energy storage the quality and reliability of the fluctuating solar irradiation is ensured. Yet without storage and no additional complementing power supplies from e.g. wind the terrestrial solar energy supply has a lower to medium supply quality and reliability mostly due to the fluctuating nature of terrestrial solar irradiation. By nature, the initial quality and reliability of the primary energy outside the atmosphere is superior.

Concerning the compatibility with existing generation and transmission systems, the major influencing parameters are the ability to integrate a single power plant in terms of power size and the requirement of further components for grid management due to feed in characteristics (such as energy storage means, backup or virtual power plants). Both the fluctuating nature of terrestrial solar power plants and the large power size of a single space based power plant require substantial enhancement of the European high-voltage transmission grid.

The environmental acceptability including public participation in the decision-making process is dominated by the quantity and the type of land area used by a single power plant, such as large-scale pumped hydro installations, large-scale SOT areas in North Africa (500 GW scenario only) and the acceptance of microwave power transmission. Discussions about space-based solar power systems comprise issues such as the experts' society and the disposal of decisions for future generations. Favorable conditions for a broad public participation of local people is especially given with the modular terrestrial solar power technologies above all with decentralized PV installations.

Fields for further research

Several issues evolved in the course of this study which could not be further assessed in detail regarding their relevance as they either were beyond the scope of the study or subject to limited time. Some of these issues are critical regarding the viability of space-based solar power systems. The following topics should thus be addressed with a high priority for further research (the list neither claims to be exhaustive nor does the order of appearance imply any priority given to a single research topic):

– Error-analysis of study results
– Update of relevant studies of area potentials for PV, SOT and SPS rectennae
– Supply / demand modeling of future European energy economy, especially considering potential supply mix scenarios and the demand for sustainable transportation fuel; consideration of a worlwide SPS energy supply option
– Update of SPS technology assessment (latest broad technology assessments dates back to [OTA 1981] and [Jochem 1988], a quantified reliability analysis is yet to come)
– Study / research of cloud covering due to climate change; effects on efficiencies of terrestrial solar power plants
– Study of the impact of air pollution ('global dimming') on the terrestrial solar power generation and microwave power transmission for the years 2030+
– Detailed technical (inter alia FMEA), economic (investors, cash-flow etc.) and environmental (see also other points) analysis of most promising system architectures and high-capacity space-transportation vehicles; validation experiments and demonstration. The best way to answer most of the technical, reliability, social and political uncertainties about space-based solar power is to build and operate a pilot plant. Nevertheless this will not answer all questions.
– Update study of the synergies and dependencies of non-terrestrial materials for space activities
– Assessment of environmental and health impacts on biosphere and atmosphere due to microwave power transmission from space as well as the feasibility to design an inherently safe microwave antenna which inherently avoids dual use

- 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.

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