SOLAR ELECTRICITY GENERATION - A COMPARATIVE VIEW OF TECHNOLOGIES, COSTS AND ENVIRONMENTAL IMPACT

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Abstract - The implementation of solar power plants in regions of high insolation is a promising option for an environmentally compatible electricity supply strategy. Today, approximately 80 % of the solar generated electricity is provided by solar thermal power plants, while 20 % are supplied by photovoltaic systems. Decision makers have the choice among the following solar technologies: 1. Parabolic Trough, 2. Central Receiver, 3. Paraboloidal Dish, 4. Solar Chimney, 5. Solar Pond, 6. Photovoltaic Cells. This paper compares present solar electricity technologies from the point of view of system analysis, taking into consideration their performance, costs and environmental impact. The study shows that the different approaches cover a wide range from units of a few watts to utility size plants and from isolated to grid connected systems. It also shows that there is still a need for intense efforts to integrate those technologies into the existing electricity supply scheme. If a continuous development and market introduction is achieved, solar power plants will contribute substantially to the reduction of global CO_2-emissions. A practical tool for decision makers is presented that facilitates a first estimate of the performance and costs of such plants under local conditions.

1. INTRODUCTION

The implementation of solar power plants in regions of high insolation is a promising option for an environmentally compatible electricity supply strategy. Today, a great variety of solar technologies for electricty generation is at disposition. Some, like the Californian 354 MW parabolic trough solar electric generating systems (SEGS), have fed more than 5000 GWh to the utility grid in more than 10 years of operating experience, supplying 80 % of today's solar electricity generation. Photovoltaic cell production has reached an annual capacity of more than 80 MW/a. Dish-Stirling and central receiver demonstration plants achieved solar to electricity efficiencies of 15 to more than 25 %. Solar chimney and solar pond demonstration plants showed reliable operation and very simple construction features that seem to be specially suited for developing countries.

The major hindrance for solar electricity implementation is the relatively high specific investment cost of the solar collector systems (Fig. 1). The availability of solar power is restricted by the natural fluctuations of the energy source. At a first glance, this seems to limit severely the possibility of generating high-revenue peak-load power as well as low-cost base load power. Finally, an important feature is the reliability of the plants that is strongly bonded to their level of development. From the point of view of utility operators, a solar plant seems to be something that is very hard to handle.

But the mentioned drawbacks can be reduced by two technical solutions:

The first solution is the hybridization of the solar power plants with fossil backup systems. A fossil backup system allows the compen-sation of solar input fluctuations and permits nighttime operation, augmenting the possible annual full load hours (capacity factor) and the power availability to more than 8000 h/a. In this case, fuel is used as additive energy source to complete the desired energy output of the plant. Parabolic trough, central receiver and dish systems allow the integration of fossil backup systems into the solar plant. Solar chimney, solar pond and pv-systems require a complete external fossil backup unit. In order to achieve a fast respond on fluctuations, the backup fuels are usually restricted to fuel oil or natural gas.

The second solution is the integration of energy storage systems into the solar plant. In combination with an augmented solar collector field, a storage allows an increase in annual solar operating hours and compensates short time fluctuations in the solar energy input. There are a number of thermal energy storage options for parabolic trough and central reveiver plants, with capacities of usually up to 12 or more hours of full load power. Solar ponds (up to 24 h) and to a lesser extent solar chimneys (approximately 1 h) have an inherent storage capacity. Dish-Stirling- and pv-power may be stored by electrochemical battery systems.

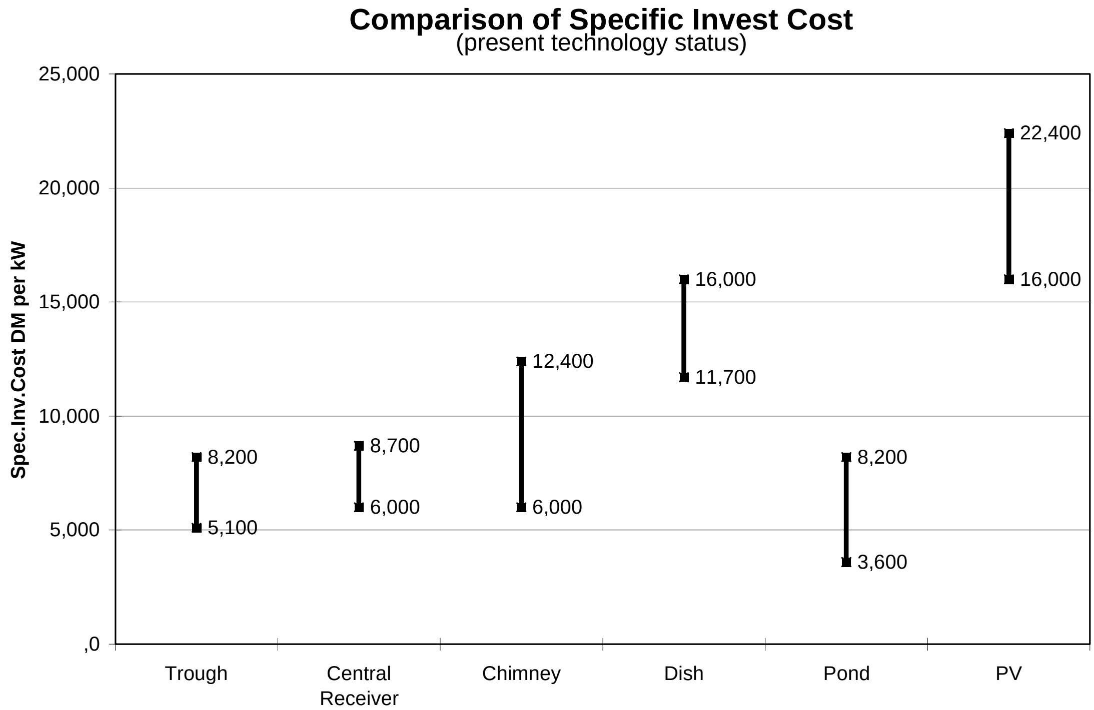

Fig. 1: Comparison of the specific investment costs of solar technologies at the present state of art

Possibly, the high specific investment cost of solar installations will become a minor problem in the future, if the production capacity of solar components increases and if the fuel costs rise; but with regard to their immediate integration into the present utility schemes, the high cost represents a severe hindrance or even a knock-out criterion. However, presently accelerating climatic changes require the quick and continuous commercialization of environmentally compatible energy technologies. Again, there are two paths that are followed to attack this problem:

Firstly, the development of low cost components has led to considerable reductions in the solar plant investment in the last 10 years and its potential is still not exhausted. But the cost development is usually contrary to the plant's efficiency, leading to a compromise between efficiency and investment. Dramatic further cost reductions are not expected until mass production of the solar components takes place, which requires their consequent and continuous worldwide introduction.

Secondly, new concepts are developed that consider solar energy for fuel saving only, not for full load capacity operation, by reducing the design solar share to well less than 100 %. This leads to a reduced collector size and hence a reduced investment in the solar field, but of course it means also reducing the fuel savings. Such concepts consider the coupling of solar thermal high temperature collectors to modern, high efficient combined cycle power plants for steam generation, for solar-chemical upgrading of the fuel or for the preheating of the combustion air. Thus, the solar-to-electricity conversion efficiency and the fuel-to-electricity efficiency is enhanced in comparison to the usual solar thermal steam cycle power plants.

The variety of solar options for power generation is sometimes quite confusing for professionals that are not familiar with this subject. The performance of solar power plants depends not only on the energy demand, but also on meteorological conditions, and of course, on its design. There are special features of each technology that are not easily comparable to other solar technologies, and much less to conventional energy systems. The following chapters describe the principles and history of the main solar electricity technologies.

2. PARABOLIC TROUGH SOLAR ELECTRIC GENERATING SYSTEM - SEGS

Solar Electric Generating Systems are designed in a power range of 30 to 150 MW. The solar receiver consists of a large array of parabolic trough reflectors that reflect the sunlight to a black absorber tube that lies in the focus line. The system cannot operate at diffuse light conditions. An automatic, one-axis tracking system keeps the tube in the focus line during the day. The absorber tube is cooled by a heat transfer fluid (HTF), usually a synthetic oil with temperature resistence up to 400 C. The hot fluid is pumped to a heat exchan-ger/evaporator of a steam Rankine cycle for steam and power generation. The fluctuations of the solar incidence power can be compensated by a fossil fuel fired backup system that consists of a HTF-heater or of a boiler integrated to the steam cycle. The backup-system is particularly important when high capacity factors and high power availability are required, which is usually the case in MW-range power plants. The backup system permits better revenues on electricity sales, because peak power can be supplied. In order to achieve a quick response on power changes, only natural gas or fuel oil are used as backup fuels. A thermal storage system can also be integrated to the plant. It is usually coupled with a larger collector field that produces additional power for some hours of storage. It allows a higher solar share on electricity production, because the plant will be able to operate on (stored) solar energy also at times without radiation (Winter et al. 1991, Becker et al. 1995, Flagsol 1994).

Before 1984, more than 10 test and demonstration facilities for solar thermal process heat generation based on parabolic troughs have been erected (Table 1). Since 1984, solar thermal trough power plants for electricity generation have been operating commercially by LUZ International Ltd. in the Californian utility grid. From 1984 up to 1991, yearly 30 to 60 MW of solar power have been added. Today, 354 MW of "Solar Electric Generating Systems" (SEGS) are installed. The originally planned amplification of installed solar capacity came to a stop in 1991, when severe changes in the Californian energy policy lead to the demise of LUZ. In spite of that, the SEGS in California have been producing more than 5000 GWh up to now and are still on the grid. With that experience, SEGS is the most developed technology for solar electricity available today. Presently there are negotiations with Morocco, Spain, Iran, Nevada, India and Israel for the implementation of further SEGS. The latest SEGS (VI - IX) reach annual solar to electricity efficiencies of 0.11 to 0.13 and maximum efficiencies of 0.15. Presently, new absorber tubes for direct steam generation (DSG) at high pressure and high temperature are developed in order to avoid the use of the HTF-loop and to achieve lower investment and operation costs (Becker et al. 1995, Flagsol 1994).

2.1 *Advantages of the SEGS-Concept*

- Reliable technology with more than 5000 GWh operating experience with the oil-cooled parabolic trough collectors
- simple hybridization with fuel oil or natural gas
- high power availability of more than 94 %
- modular solar components with high mass production potential
- simple operation strategy
- cogeneration is possible.

2.2 *Disadvantages of the SEGS-Concept*

- Solar operating temperature restricted to 400 C
- steam temperature restricted to 370 C in solar mode (510 C in fuel mode)
- the solar energy and the fossil backup energy are converted to electricity with a relatively low steam cycle efficiency
- the collectors require very stable supports for the mirrors
- considerable thermal inertia of the HTF loop
- high cosine losses due to one-axis tracking
- water needed for cooling and cleaning (alternatives are available).

3. CENTRAL RECEIVER POWER PLANTS

In this concept, the collector consists of a large, two-axis tracked field of mirrors (heliostats), that reflect the sunlight (only beam radiation) to a centrally placed receiver mounted on the top of a tower. Different absorber concepts have been tested: direct steam generating tubular receiver, open volumetric air receiver, molten salt tubular or film receiver and others. Usually, a conventional steam cycle power plant is connected for the heat to electricity conversion. The air system allows operating temperatures of up to 800 C, enhancing clearly the steam cycle efficiency. A heat storage can be incorporated to the system to atenuate solar input fluctuations and to enhance the solar energy harvest. The molten salt concept is specially suited for efficient heat storage. Hybridization of the power plants is possible, using fuel oil or natural gas as backup. The typical power range is 30 to 160 MW (Becker, Klimas 1993).

Since 1980, eight experimental and demonstration plants for central receiver technology have been erected (Table 2). The largest plant was the 10 MW Solar One at Barstow, California, with a direct steam generating absorber. Presently, the plant concept is changed to operate with a molten salt receiver (Solar Two). An open volumetric air receiver was proposed by the PHOEBUS Consortium consisting of European companies and research institutions. The consortium finished a feasibility study in 1990 and considered building a 30 MW plant in Jordan. The demonstration of a volumetric air receiver in a medium scale (2,5 MWth) was carried out successfully at the CESA-1 facility at the Plataforma Solar de Almeria, Spain in the frame of the Technology Programme Solar Air Receiver (TSA). Further development of the air receiver is leading to ceramic receivers for higher temperatures and to a closed cycle, which requires a quartz glass window in front of the absober material. SODEAN, Spain, is presently elaborating a feasibility study on a hybrid combined cycle power plant for cogeneration of electricity and heat, based on a direct steam generating central receiver.

3.1 *Advantages of the Central Receiver-Concept*

- High solar efficiencies
- high steam temperatures
- simple hybridization with fuel oil or natural gas
- high power availability of more than 94%
- modular solar components (heliostats) with high mass production potential
- simple operation strategy
- process steam generation for eventual cogeneration.

3.2 *Disadvantages of the Central Receiver-Concept*

- Thermal energy losses and parasitics (blower) due to the open air cycle (PHOEBUS)
- the solar energy and the fossil backup fuel are converted to electricity with a relatively low steam cycle efficiency
- the heliostats require very stable supports for the mirrors and two axis tracking
- water needed for mirror cleaning (alternatives are available).

4. SOLAR CHIMNEY POWER PLANT

If a flat area exposed to the sun is covered by a glass cover, the soil and the air underneath the cover will heat up to approximately 35 C over ambient temperature: the greenhouse effect. If the roof is given a slight inclination towards the center and a high chimney is installed there, the hot air will rise up and a stream with up to 15 m/s wind speed will develop at the entrance of the chimney. This stream can be used for electricity generation by means of a horizontally rotating wind generator. The principle of operation of the collector permits the use of diffuse and beam radiation. The soil under the transparent cover acts as a heat storage enabling the plant to work at reduced power for some hours after sunset. A solar chimney power plant can be designed for a power of 30 to 100 MW (Schlaich 1994).

The first experimental plant with 50 kW electrical power was built 1981/82 in Manzanares, Spain, sponsored by the German Government and operated in cooperation with the Spanish utility Union Electrica Fenosa. The chimney had a height of 200 m, the collector covered 45000 m^2. Extensive experience has been gained in the seven years of operation between 1982 and 1989. Between 1986 and 1989, the plant was connected to the utility grid. In 1987, the system reached 3157 working hours including 244 hours at night. The Manzanares prototype was removed after the experimental period.

4.1 *Advantages of the Solar Chimney-Concept*

The glass collector uses diffuse and beam radiation
the soil under the collector acts as heat storage, avoiding sharp fluctuations and allowing power supply after sunset
easily available and low cost materials for construction
simple fully automatic operation
no water requirements.

4.2 *Disadvantages of the Solar Chimney-Concept*

Very low solar to electricity conversion efficiency
hybridization is not possible
equivalent full load hours restricted to approximately 2500 h/a
large, completely flat areas required for the collector
large material requirement for the chimney and for the collector
very high chimneys necessary for high power output (e.g. 750 m for a 30 MW plant).

5. DISH-STIRLING SYSTEMS

In this system, the solar collector (paraboloidal dish reflector) and the heat-to-electricity conversion system (Stirling Engine) are mounted on one single rack. The two-axis tracked device can use only direct beam radiation for electricity generation. The heat absorber of the Stirling engine, usually a tube- or a heat-pipe-absorber, is placed in the focal point of the dish reflector. It is cooled by gaseous hydrogen or helium, the usual working fluids for Stirling systems. The Stirling engine is an externally heated hot gas engine with reciprocating piston that operates in a closed four step regenerative thermodynamic cycle. Stirling engines have multi-fuel capacity, high efficiency, low emissions, long life and operate very quietly. Dish-Stirling systems are highly modular, stand-alone units of 10 to 50 kW of power that can be connected to form larger grid connected electricity plants of more than 1 MW. Hybridization is possible but has not yet been realized (Stine and Diver 1994).

Six units of smaller streched membrane dish-Sirling systems with 9 kW power using the Solo V-160 engine were built by Schlaich, Bergermann and Partner (SBP) of Stuttgart, Germany in 1991 and erected in Almeria, Spain and in several sites in Germany (Table 3). The V-160 Stirling engine has a working temperature of 620 C. The overall solar to electric conversion efficiency is maximum 0.203. Cummins Power Generation, Inc. (CPG) of Columbus, Indiana, USA is the first company in the world using a free-piston Stirling engine for solar electric power generation. Cummins is currently testing three 5 kWe prototypes. The design solar to electricity efficiency is over 0.19. Sunpower, Inc. is developing the 9 kWe free-piston Stirling engine with a linear alternator for use in this system. The working gas is helium at 629 C. Aisin Seiki Co., Ltd., of Kariya City, Japan, built the NS30A engine with 30 kWe under the Japanese government's New Energy and Industrial Development Organization (NEIDO) project. The four-piston double-acting engine operates on helium at 683 C. One of these units has been tested with a McDonnel solar concentrator at Kariya City. Three further engines derated to 8.5 kW with Cummins CPG-460 stretched membrane concentrators are used for generating electric power on Miyako Island, 290 km southwest of Okinawa. To provide power after sunset, a electrochemical zinc-bromine-battery with a capacity of 30 kWh is incorporated to each system. Stirling Thermal Motors Inc. of Ann Arbor, Michigan and Detroit Diesel Corp. of Detroit, Michigan, have designed a solar power generating system incorporating the STM4-120 Stirling engine with 25 kWe power. The completely self-contained package is suitable for integration with a variety of solar concentrators.

5.1 *Advantages of the Dish-Stirling-Concept*

Completely autocontained stand-alone units
very high concentration ratios, working temperatures and efficiencies
long-term experience with small scale power plants and single units
options for distributed as well as centralized electricity supply systems
modularity of the system, benefits of mass production, no scale restriction
simple operation and maintenance.

5.2 *Disadvantages of the Dish - Stirling - Concept*

integrated fossil backup not available until now
low power availability and few annual full load hours
requires rigid support structures and perfect tracking that leads to high costs
no experience with large utility scale systems
water requirement for cleaning.

6. SOLAR POND POWER PLANTS

A salt gradient solar pond is an usually large reservoir of water with a black bottom absorbing the solar diffuse and beam radiation and transforming it to heat in form of hot water. In order to avoid internal convection and heat losses through the surface, the pond is devided into three typical zones:

A narrow convective top layer of low density water with low salt concentration. Convection in this layer is caused by wind and surface losses.

A 1 to 1.5 m deep non-convective zone with downwards increasing salt concentration. The salt gradient avoids the rising of lower, warmer layers of water. Thus, this layer acts as transparent insulation for the pond, admitting the sunlight to pass to the lower zones but avoiding heat convection from the bottom to the top.

A bottom layer of 2 to 4 m depth with very high, in some cases saturated salt concentration. The specific weight of the water in this layer is extremely high, thus preventing it from rising to the upper layers when it heats up. Inside this zone, the salt concentration is constant, so that the heat will be distributed uniformly by internal convection. The thickness of this layer will define the storage capacity of the pond.

Taking advantage of this principles, the upper convective zone will stay cold even if the bottom zone has a temperature of 90 C or more. Thus the thermal losses are kept small. The water from the storage zone is withdrawn and pumped to a heat exchanger that acts as evaporator for an organic Rankine cycle (ORC). The organic working fluid with low boiling point allows the operation of the Rankine cycle at temperatures under 100 C. ORC reach conversion efficiencies of 8 %.

The salt-gradient solar pond was discovered as a natural phenomenon in 1902. Scientific Research Foundation (SRF) and Ormat Turbines Co. of Yavne set up a Company in 1977, Solmat Systems, which built a 150 kW demonstration plant at Ein Boqek at the shores of the dead sea (Table 4). The plant was coupled to the Israeli electricity grid in 1979 and worked successfully for seven years. The experience gained with that system led to a 5 MW SPPP-project in Beith Ha'Arava in 1984, partially sponsored by the Israeli government. Because of budget restrictions, to pond surface (210 000 m^2) was extended only to a quarter of it's design area (1 km^2), but operation could be demonstrated successfully. Other smaller solar pond power plants were erected in Alice Springs, Australia in 1985 and in El Paso, Texas, USA in 1986. The El Paso project included cogeneration of electricity (70 kW) and process heat (330 kW) for desalination (Tabor 1990).

6.1 *Advantages of the Solar Pond-Concept*

Unique storage capability inherent to the plant concept
suitable for peak, intermediate and base load operation in solar only mode
suitable for cogeneration of process heat and electricity.

6.2 *Disadvantages of the Solar Pond - Concept*

Very low solar to electricity efficiency
high land requirement
considerable remake water and high quality salt needed
difficult stabilization of the salt gradient in windy areas
difficult maintenance of the immersed pipework
very long construction and setup time for large ponds.

7. PHOTOVOLTAIC POWER PLANTS

Photovoltaic cells are semiconductor devices capable of converting sunlight into direct current. The most important solar cell material is Silicium in monocrystalline, polycrystalline, amorphous or thin film structure. Solar cells accept beam as well as diffuse insolation for electricity generation. The cells are encapsulated in modules that can be connected in series and in parallel forming groups of high voltage and power up to utility scale. Usually, the modules are arranged in groups of some kilowatt that are connected individually to a dc-to-ac-inverter with maximum power point tracker. Those groups are arranged parallely in larger arrays delivering power to the grid connected transformer station. The modules can be mounted on a fixed rack or on a sun tracking device. Pv-stand-alone systems need an additional battery for energy storage or a conventional backup system (e.g. Diesel Generator) in order to achieve a sufficient and reliable power supply in periods of low radiation intensity.

Solar cells were developed in the early space research programms of the 50s and 60s. Adaptation to terrestrial applications took place after the energy crisis in the early 70s. Since then, a continuous increase in the worldwide production has been registered, reaching today an annual production capacity of more than 80 MW/a (Johansson 1993). While the main market remains for decentral small size applications, also some grid connected systems in the megawatt-range have been erected for investigation and demonstration purposes (Table 5).

Germany, Switzerland and Austria had in the last years pv-dissemination programmes for distributed 1 to 5 kW grid connected pv-systems in order to promote pv-system development and marketing. Japan is presently developing a similar programme. The European Union also encourages and sponsors projects for pv-integration (Langniß 1994).

7.1 *Advantages of the Photovoltaic Power Plant- Concept*

No movable parts
long operation lifetime
low maintenance
options for distributed as well as centralized electricity supply systems
modularity of the system, benefits of mass production, no scale restriction
long experience in pv-technology, commercial components.

7.2 *Disadvantages of the Photovoltaic Power Plant- Concept*

Relatively low efficiency
in spite of a yearly 80 MW production, the pv-investment cost is still very high
annual full load hours are restricted
no hybridization possible, only complete fossil backup systems or grid connected
electrochemical storage options are also very expensive.

8. SYSTEM COMPARISON

The different concepts of solar electricity generation are represented by selected "reference plants" that are considered typical and state of the art. The available data correspond to specific case studies or performance reports. This implies, that the meteorological, operational and demand side conditions are quite different for the selected systems (Table 6), which makes it difficult to compare them directly. Nevertheless, some general conclusions can be derived from these data.

The best annual solar to electricity efficiencies are achieved by the concentrating systems (dish-Stirling (16%), parabolic trough SEGS (14.9 %), PHOEBUS central air receiver (14.1 %)) with a corresponding relatively low land requirement for those plants.

Only the hybrid concepts (trough, central receiver) offer high power availability for base load and peak load operation, which makes them the most suitables for utility application.

Due to their large inherent storage capacity, solar ponds have also a relatively high power availability. Hybridization of a solar pond is possible but not feasible because of the low efficiency of the ORC. A major drawback of solar ponds is their high water and salt requirement for the make up of the salt gradient zones. This limits their application to areas where water as well as salt are easily available.

The solar chimney was calculated with glass, steel and concrete prices for Southern Europe. In developing countries with a much lower price and salary level, the plant's costs may scale down to lower values, because those materials usually can be produced on national level.

The most suitable technologies for small and medium stand-alone applications are pv- and dish-Stirling systems, normally in combination with an electrochemical storage battery. If a high power availability is required or if the plants are operating in a decentral grid, a fossil fired backup unit must be installed additionally.

The emissions of the plants are compared to an arbitrarily defined "present energy system", which is characterized by a typical specific CO_2-emission of 1.05 kg/kWh. Naturally, only the hybrid systems produce emissions to the atmosphere.

Table 6: Performance, cost and environmental impact of selected reference systems (costs in German Marks (DM) 1995, electricity cost in first year operation, interest rate 7 %, contingencies 10 % of investment included, fuel prices: natural gas 9 DM/GJ, fuel oil 6.8 DM/GJ).

The comparison shows that each technology has its strenghts and weaknesses, and a final decision pro or contra can only be taken considering the special circumstances at each site. Moreover, each base technology (trough, central receiver, chimney, solar pond, pv) has advanced variants with different performance and costs. In order to get an overview, a decision maker is forced to consult specialists on each technology. That is a time and money consuming process.

9. THE SPREAD SHEET CALCULATION PROGRAMME "SOLELE"

SOLELE is a tool for the comparative evaluation of solar electric systems. It is meant for the use by decision makers in the electricity sector and allows a first estimate of the performance, costs and environmental impact of the different concepts of solar power plants.

An advantage of SOLELE is its speed and simplicity, since it is not based on the usual (time-step) simulation of the solar power plant operation, but on up and down scaling of its main performance parameters, parting from the behaviour of a known "reference plant" under known environmental and economical conditions. The programme is a LOTUS 1-2-3 compatible spread sheet.

The parameters that can be varied by the user are devided into three categories:

Eligible Design Data, including the selection of the preferred plant type, its rated power, desired annual full load hours, desired design point solar share (which may be lower than the maximum possible solar share), storage capacity, and the available local annual global radiation.

General Economic Parameters, like salaries, fuel costs, present electricity cost and other economical parameters.

Environmental Data of the present Energy System or any other user-defined reference system. Parameters are the mean specific fuel consumption and the emission rates of CO_2 and other energy related pollutants.

The results for the specific plant are displayed in a condensed form on a page called **"Summary"** and in four graphics that show the plant's emissions and its specific fuel consumption, electricity cost and CO_2-avoidence cost as a function of the annual equivalent full load operating hours of the plant. This feature is particularily interresting for hybrid fossil-solar power plants. Additional pages give more detailed informations.

The "scaling" approach allows a very quick and simple extrapolation of the plant's performance under others than the "reference" conditions, using very few characteristic parameters for the calculations. Of course the accuracy of this method is limited, but it is sufficient for a first estimate. The programme allows an easy understanding of the correlations of the parameters influencing the solar plant's design and performance, which makes it quite suitable for training purposes.

At present, the programme is working under LOTUS 1-2-3, Version 4 and compatible spread sheets. Costs are calculated in German Marks (DM) for 1995, because a considerable share of German technology is involved. The adaptation for other currencies and spread sheet formats is under process. Presently, the tool is in the first evaluation phase. It includes the following reference plants:

Parabolic Trough System with HTF-Loop coupled to a Rankine Cycle (SEGS)

Central Volumetric Air Receiver coupled to a Rankine Cycle (PHOEBUS)

Dish-Stirling System with Stretched Membrane Concentrator (SBP)

Solar Chimney Power Plant

Salt Gradient Solar Pond Power Plant (SPPP)

Photovoltaic Power Plant with Monocrystalline Solar Cells

The programme is delivered together with a brochure that describes the history and status of each technology and the performance of the reference plants. In the near future, it will be extended to advanced systems like direct steam generating troughs, as well as to solar combined cycle and solar cogeneration systems. Of course, the programme will be updated continuously considering new developments and changes in efficiencies or component costs.

10. CONCLUSIONS

The great variety of options for solar electricity generation is very promising, but also quite confusing for decision makers that are not familiar with solar technologies. The presented paper and the calculation programme SOLELE are meant as a contribution to facilitate a systematic comparison of the diverse existing solar technologies under economical, meteorological and operational frame conditions that are freely selectable according to local circumstances. The programme does not replace the necessary consulting of specialists for the assessment and design of solar power plants, but it allows a preliminary selection of possible and feasible options, and gives an estimate of the costs and benefits of the plants for a wide range of possible regions and application cases.

Variations of the solar incidence, the rated power, the capacity factor, component costs etc. facilitate the understanding of the correlations between the main plant parameters, which makes this tool suitable for training and renewable energy education purposes.

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