Status Report on Solar Trough Power Plants

- Experience, prospects and recommendations to overcome market barriers of parabolic trough collector power plant technology -

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The commercialization of solar thermal electric technology took a major step forward in the mid-1980's and early 1990's with the development of the SEGS plants in California by Luz International Ltd. Consisting of parabolic trough technology integrated with steam Rankine cycles, these facilities total 354 MW of installed capacity and have 72 plant-years of operation to date. Together they have provided a wealth of operating experience and instilled confidence in a wide spectrum of observers on the viability of solar thermal technology as a future power source. From this base a number of feasibility studies and development programs have been launched to develop new projects and further advance the technology. To date, however, no new facilities have been implemented despite these efforts and the encouragement of institutional and governmental sponsors.

Two important goals of this document are to explore the status of solar thermal power plant development and to provide some insight into actual and perceived barriers delaying the commercial advancement of this technology. As background, the technology is described starting with a brief overview of solar technologies, and the potential market for solar thermal plants is postulated. Integral with market considerations are an understanding of world energy and electricity growth projections, and the associated impact on the environment and global warming through emissions, both of which are treated. Technology costs, economics and financing of commercial-scale plants are discussed and recent feasibility studies and results are presented. Finally, policy recommendations and financing scenarios are postulated which could ease the path for further commercialization and accelerate future implementation.

Joachim Benemann
President

January 1996

PILKINGTON

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1. Why Solar Thermal Power Plants?

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1. Why Solar Thermal Power Plants?

One of the most controversial public debates of the last decade has addressed the effects of energy-related emissions on the environment. Serious and widespread recognition and alarm have centered on air quality and, in a more global context, the greenhouse effect and the destruction of the protective ozone layer of the earth's atmosphere from CO_2 and other gases. Air quality is primarily affected by SO_2 and NO_X emissions which cause acid rain and smog. A focal point of the debate has been future energy supply strategies, including the use of environmentally benign energy conversion technologies. Key issues have been the future role of nuclear energy and the strong public desire to rapidly introduce renewable energy technologies on a large scale to ensure sustainable energy growth without harmful societal impacts.

The promise of renewable energy to play a major role in the solution of the environmental crisis has elements of both reality and myth. Renewable technologies such as solar power and wind energy are synonymous with the desire for an environmentally responsible energy supply. Nevertheless, at present solar and wind contribute only marginally to the world's electricity production.

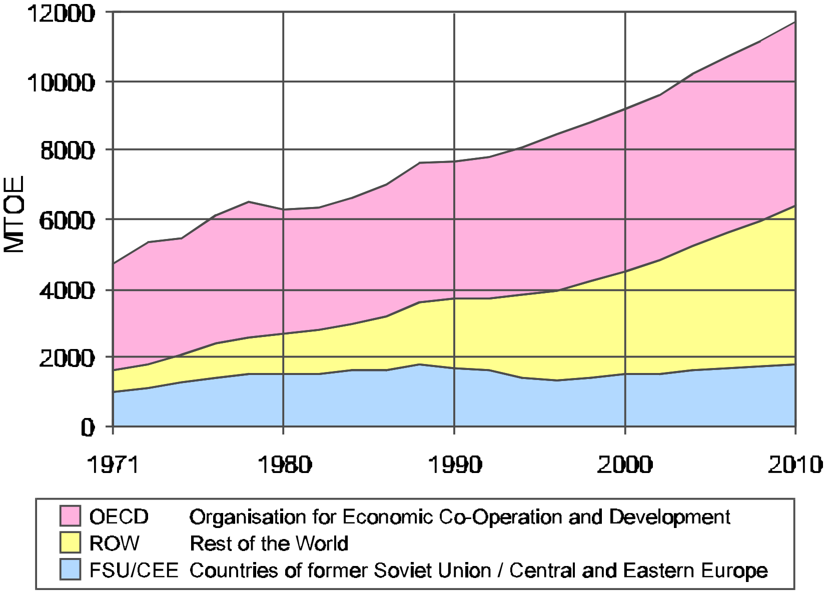
Whereas photovoltaic power generation is often viewed by the public as the emerging solar technology, it is in fact other renewables - notably wind energy, biomass and parabolic trough solar thermal power plants - which produce far more power today. More than 70% of the present production of the world's electricity produced directly by solar radiation is generated by solar trough plants in the California Mojave desert.

The promise of renewable energy to solve the environmental crisis has elements of both myth and reality - we argue that solar trough plants have the potential to regionally displace significant fossil-fired power generation

1.1 The Evolution and Dimension of Global Energy Demand

As a result of the public concern about energy-related emissions, it is generally acknowledged that a key objective of global energy policies should be a significant reduction of emissions, specifically of the greenhouse gas CO_2. Note, in particular, the creation of the important Global Environment Facility (GEF) at the United Nations Conference on Energy and Development (UNCED) in Rio de Janeiro in 1992 with the goal of supporting the implementation of energy efficiency measures and renewable energy technologies. In addition, the World Bank has recently proposed a "Solar Initiative" to support the initial market entry of renewables. In actuality, however, global trends are contrary to the goal of emissions reductions, with data showing an increasing level of CO_2 emissions driven by a strong growing demand in primary energy.

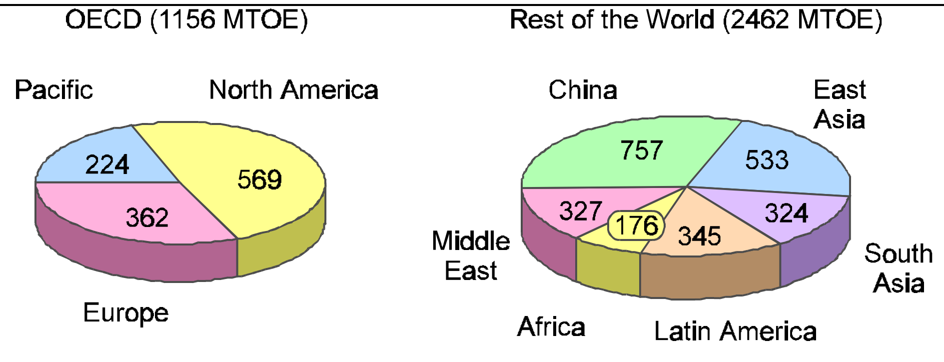
The World Energy Outlook of the International Energy Agency (IEA) gives an insightful picture of energy growth expectations over the next 1-1/2 decades.



Source: IEA "World Energy Outlook" 1994

Figure 1-1 World Total Primary Energy Demand Evolution (in Million Tons of Oil Equivalent - MTOE)

The dimension of the energy need, specifically for the developing world and the emerging southeast and east Asian markets, emphasizes the critical importance of tackling the greenhouse effect. By 2010, the world will be consuming 48% more energy than in 1991 (Figure 1-1). The increase in energy use forecast for the rest of the world is expected to be even more pronounced than in the OECD. In these countries, particularly in China and the dynamic economies of East Asia, the average annual growth in energy use during this period could be more than 4% per year. (Figure 1-2)

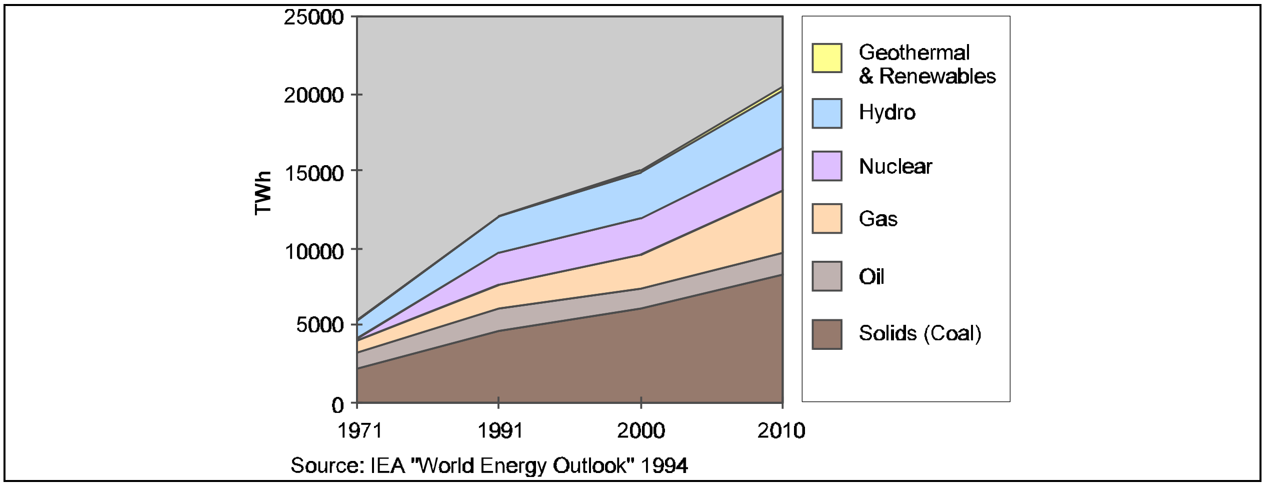


Source: IEA "World Energy Outlook" 1994

Figure 1-2 Incremental Primary Energy Demand 1991-2010 (in Million Tons of Oil Equivalent)

Electricity is the most rapidly growing form of end-use energy with an increase of about 70% at the end of the time horizon. In many countries, the growth of electricity will keep pace with or exceed GDP growth. Figure 1-3 shows electricity demand growth by fuel category.

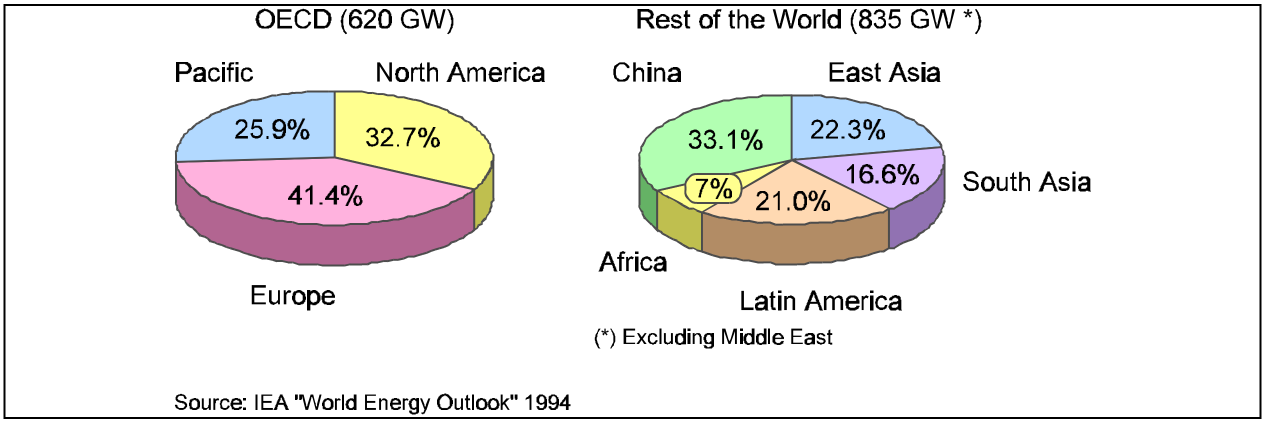
Fossil fuel based generation capacity will grow faster than power generation from nuclear and hydro in the OECD countries due to limited expansion possibilities, specifically caused by permitting problems for nuclear and a saturation in the development of hydro electric power. In the rest of the world, incremental electricity demand will be mainly met by fossil fuels.



Source: IEA "World Energy Outlook" 1994

Figure 1-3 World Electricity Demand Evolution by Type of Fuel

Demand growth is particularly significant in the ROW (rest of the world) sector where per capita consumption will double by the year 2010. Consequently, by 2010 global power generation capacity will increase by 620 GW in industrialized countries and 835 GW in the rest of the world, as shown in Figure 1-4.



Source: IEA "World Energy Outlook" 1994

Figure 1-4 Incremental Power Generation Capacities (1991-2010)

Because of the limitation on hydro electric and nuclear power generation in the OECD regions, renewable electricity generation is expected to grow strongly there at an average of about 9% per year, thus producing 70% of the world's renewable electricity by 2010. Although Latin America, Africa and Asia offer excellent conditions for the exploitation of renewable electricity, their contribution is considered to rise less rapidly, according to the IEA's projection. Although renewable energy technologies, basically geothermal and biomass plants, wind energy and some solar, will more than quadruple their electricity output from today's 40 TWh to approximately 190 TWh in 2010, their contribution to total power production will only rise to about 1%. However, even this marginal contribution represents an additional renewable capacity of approximately 25,000 MW during the next 15 years.

1.2 The Environmental Challenge of Energy Production

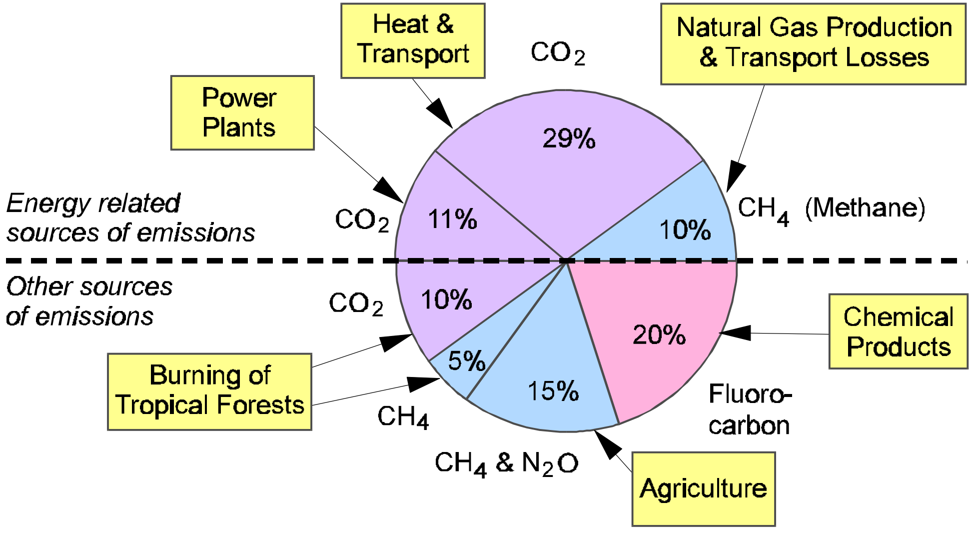
90% of human energy needs are satisfied either by burning commercial fossil fuels (coal, oil and gas) or by burning traditional, renewable energy sources such as fuel wood, dung and other types of biomass. In the combustion process CO_2 is formed and discharged to the atmosphere. Part of this CO_2 is converted by photosynthesis or absorbed by the oceans, with the remainder increasing the CO_2 concentration in the atmosphere. From pre-industrial times to the present, the CO_2 concentration in the atmosphere has risen from 280 parts per million (ppm) to close to 360 ppm. It is currently increasing at an accelerating rate which is now about 3 to 5 ppm per year.

Possible Effects of Increased CO_2 Levels

Although the physics and chemistry of the earth's atmosphere are not sufficiently understood to draw precise conclusions about the effects of an increase in CO_2 on climate, the scientific community almost unanimously concludes from theoretical models that a temperature rise of 0.1°C in ten years can be expected. However, feedback mechanisms could considerably speed up the rise of CO_2 concentrations in the earth's atmosphere. The Advisory Group to the German Federal Government wrote as early as February 1988:

> ***The possibility can no longer be excluded that within the coming decades up to the middle of the next century, the content of CO_2 in the atmosphere could reach such a level that an intensified greenhouse effect could cause a global rise in mean temperature of several degrees centigrade. In turn, this would lead to dramatic and irreversible climatic changes and displacements of climatic zones whose effect over large parts of our planet are as yet uncertain but are likely to be negative.***

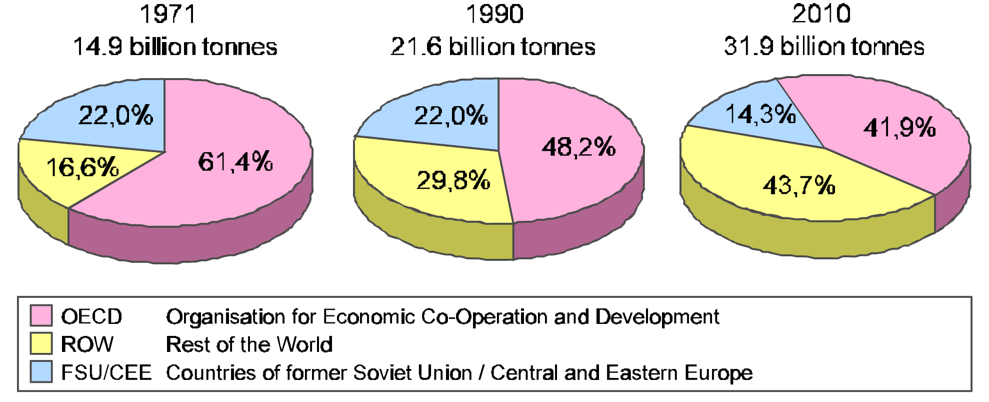
Figure 1-5 illustrates the relative contributions of different energy uses or sources to the global greenhouse effect. Energy-related CO_2 emissions are the largest single source. Power, heating and transportation contribute about 40%, with another 10% added from methane due to losses in natural gas production and transport.



Source: Final Report of the Federal German Government's Parliamentary Enquête Commission: "Protection of the Earth Athmosphere", Bonn 1995

Figure 1-5 Climate Relevant Gases by Sectors and Sources and their Specific Contribution to the Global Greenhouse Effect

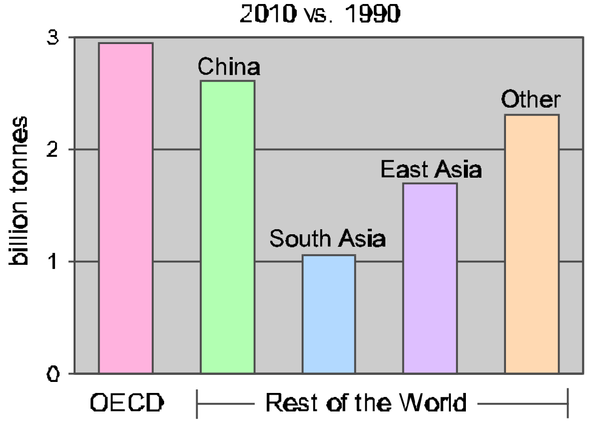
On the other hand, growth in the energy sector is a pre-requisite for economic development and welfare of nations. Even though reductions in CO_2 emissions are imperative, extrapolation of the trend of global CO_2 emissions due to increased energy use shows an increase from approximately 22 billion tons of CO_2 in 1990 to 32 billion tons of CO_2 in the year 2010, an increase of 47%. Figure 1-6 classifies this growth by major political regions of the world.



Source: IEA "World Energy Outlook" 1994

Figure 1-6 Development of CO_2 Emissions by Regions

It is particularly disturbing that CO_2 emissions will rise by 28% in the OECD countries despite the reality that the richer OECD countries can better afford energy efficiency programs and the introduction of more costly but cleaner energy technologies. The situation may be of greater concern in the developing world. Figure 1-7 plots the <u>increase</u> in CO_2 emissions between the years 1990 and 2010. The group of countries (ROW) will more than double their CO_2 emissions, mainly through their accelerated use of fossil energy to keep pace with the energy demand of their rapidly growing economies.



Source: IEA "World Energy Outlook" 1994

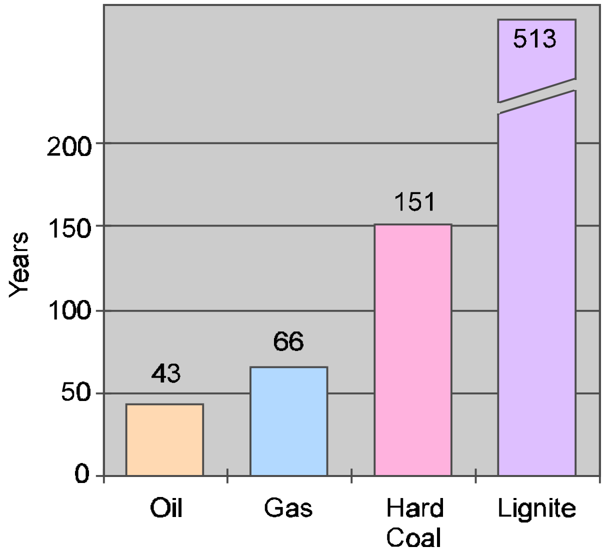
Figure 1-7 Increase in Annual CO_2 Emissions

It is clear that energy and the economy are facing great challenges with respect to climate and environment. The implementation of cleaner energy technologies and development of renewable energy sources is essential in order to close the gap between the competing needs for additional energy and reduced CO_2 emissions.

1.3 Introducing Renewables - A Strategic Hedge against Fuel Price Risks

The modern development of renewable and specifically solar energy technologies in the 1970’s began as a result of the finite availability of fossil fuels, specifically crude oil and natural gas. Today’s global energy economy will continue to rely predominantly on fossil fuels through the first decades of the next millennium.

Under static conditions of increase in demand and production, fluid hydro-carbon reserves of oil and gas will be exhausted in 4 and 6-1/2 decades, respectively, at today’s depletion rate and price level (Figure 1-8).



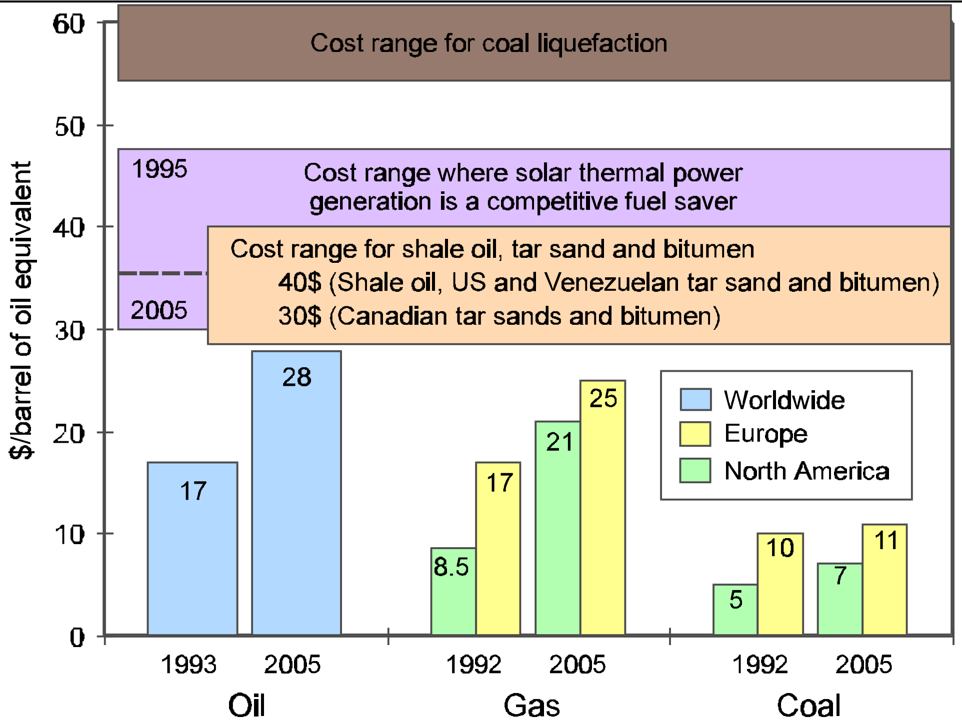
Source: German Mining Yearbook and RWE, 1994

Figure 1-8 Range of Global Reserves of Fossil Fuels at Current Depletion Rates

These reserves can be prolonged when using so-called unconventional primary resources like shale oil, oil tar and bituminous oil reserves. Making these additional primary resources available will increase production prices to about 30 to 40 USD per barrel of crude oil equivalent.

The other huge fossil reserve, coal, will last about 200 years or so but its use contributes to the greenhouse effect. Specific CO_2 emissions for coal are 30 to 80% higher than for oil or gas, respectively. One strategy proposed to reduce these emission levels is coal gasification, with the gas being used in efficient combined cycles. However, gasification does not alleviate the specific CO_2 emissions issue, and the use of gasified coal in combined cycles is less effective by about 10 percentage points than the use of natural gas. Hence coal is expected to play a less dominant role in a future environmentally-driven energy supply scenario.

In such a scenario, coal will regain dominance if oil and gas supplies become scarce and renewables have not gained extensive use. Once the liquid fossil fuels are exhausted coal liquefaction might become of strategic importance. Liquefied coal production prices might then be expected to rise to 60 USD per barrel of oil equivalent.



Source: IEA "World Energy Outlook" 1994 and own calculation

Figure 1-9 Anticipated Fossil Fuel Prices and Cost of Back-Stop Technologies

With such price levels for fossil fuels, renewable technologies become increasingly competitive. Today, solar thermal power generation can competitively replace fossil based power generation at fuel price levels equivalent to 35 - 45 USD per barrel, depending on radiation, infrastructure and operational mode. With an initial technology implementation rate higher than the present 354 MW_e, this price level can be lowered to approximately 30 USD or less, as depicted in Figure 1-9.

With rising price for fossil fuels over the next 1-2 decades, renewable technologies will become increasingly competitive

1.4 Solar Thermal Power Plants and the Solar Resource

Renewable energy technologies consist of *primary* solar systems using the sun's radiation directly, such as solar thermal power and photovoltaics, and those using the *secondary* effects of radiation such as wind and biomass. In a strict sense hydro power is another secondary solar system. The principles and operating experience of the primary solar renewable technologies are described and discussed in section 3. One characteristic of renewables is the intermittence of the resource, e.g., photovoltaics generate electricity when the sun is available and wind machines need a sufficiently high wind to produce power. Of the primary solar technologies, only solar thermal systems can generate electricity whenever it is needed because it can be configured in a hybrid system which allows the use of an integrated supplementary fossil fuel source. This ability to meet capacity on demand is an important feature of a power plant. The additional cost to gain this advantage is typically low. Of the secondary systems, also biomass combustion systems feature a hybrid concept with the ability to burn additionally fossil fuels.Hydro power plants can also provide capacity on demand as long as the storage facilities (e.g., reservoirs) are large enough.

The ability of solar thermal system to also use fossil fuel means that peak electric output can always be assured at a low incremental investment cost

If renewable technologies are to respond to the environmental challenge, they must be able to contribute to future electricity production to the extent that CO_2 emissions can be reduced on a global scale. Solar electricity has a large potential due to the uniformity and sheer magnitude of its primary source over the majority of world regions.

As discussed in section 3, solar technologies using concentrating systems for electrical production require sufficient direct normal radiation, which is the beam radiation which comes from the sun and passes through the planet's atmosphere without deviation and refraction. (Although total solar radiation is also high in the tropics, the beam component is low and thus these areas are not appropriate for solar thermal power plants.)

Consequently, appropriate site locations are normally situated in arid to semi-arid regions. On a global scale, the solar resource in such regions is very high. More exactly, acceptable production costs of solar electricity typically occur where radiation levels exceed about 1700 kWh/m^2-yr, a radiation level found in many areas as illustrated in Figure 1-10. Appropriate regions include the North African desert, the Arabian peninsula, major portions of India, central and western Australia, the high plateaus of the Andean states, northeastern Brazil, northern Mexico and, of course, the southwest United States. Promising site locations in Europe are found in southern Spain and several Mediterranean islands.

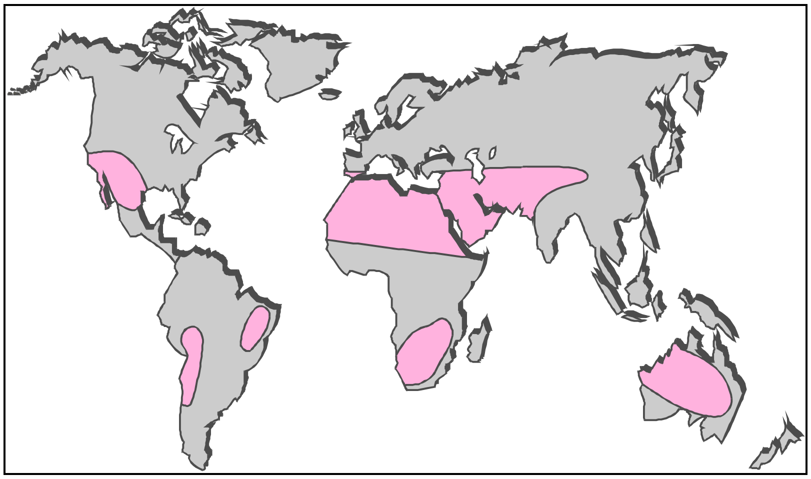


Figure 1-10 Favorable Regions for Solar Thermal Electricity

To emphasize the magnitude of the solar resource, an illustrative calculation is useful. This is shown in Table 1-1 which gives a conservative estimate of the potential of the global solar resource available for conversion to solar thermal power production. Note that even with the assumption that only 1% of the land area in the world which has sufficient solar radiation is used for solar power plants, the potential annual electricity generation is still larger than the projected total world electricity production in the year 2000. While there are practical reasons which prohibit development of this full potential, the point is clear that the solar resource is great and can make a very significant contribution to world electricity production.

1. Global solar radiation on the world’s land area	240×10^{6}	TWh/yr
2. Desert areas occupy 7% of the world’s land area (assuming equal distribution of solar radiation)	16×10^{6}	TWh/yr
3. Useful direct normal fraction of incoming radiation (about 70%)	11.2×10^{6}	TWh/yr
4. Average annual solar-to-electric conversion efficiency (average 15%)	1.68×10^{6}	TWh/yr
Portion of semi-arid and arid sites for solar plants in areas of habitation and access to infrastructure (1% of desert areas)	16.8×10^{3}	TWh/yr
Total world electricity production in 2000	15×10^{3}	TWh/yr

Table 1-1 Potential of Solar Thermal Power Generation in High Radiation Areas

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2. A Difficult Power Market for Solar Electricity

The expected growth in the world energy demand and the environmental challenge associated with this growth calls for the rapid and large scale introduction of renewable energy technologies. Over the next 1-1/2 decades electricity production is expected to grow by 70% while total primary energy demand will increase by 47%. Power generation with markedly reduced emissions will invariably be necessary to control the greenhouse effect. Renewable energy systems will play a key role in achieving this goal. Among the variety of promising renewable power concepts, solar electricity from solar thermal and photovoltaic systems is expected to have the largest potential due to the abundant solar resource which offers 10,000 times more radiation energy than the world actually needs as primary energy. Although efficient direct solar electricity production is basically restricted to the so-called sun belt of the world, i.e., that region situated between 15° to 35° latitude in both the Northern and Southern hemispheres, this is in fact the area with the largest increase in demand for primary energy and electricity.

Renewable energy systems will be vital for the reduction of emissions over the next several decades

[LAYOUT: Separate box!]

Evolution of the Electricity Sector in Developed and Developing Countries

Since the beginning of this century, electricity has been regarded as a strategic form of energy able to power equipment, provide lighting and supply heat. Although the success story of electricity started with private initiatives, power generation was soon recognized to be a matter of governmental concern due to the tremendous investments needed to build up the necessary infrastructure. Most of the electric utility companies in the industrialized world were protected by governmental regulation to ensure long-term pay-back of the initial investment. Typically regions of supply were defined where a specific electric utility acted as a monopoly. Tariffs were subject to governmental approval.

This tendency was even more pronounced in the developing world when the electricity sector was built up in the 50’s and 60’s of this century as many countries became independent. The power sector was commonly structured to be administered by a ministry of energy or electricity, and wholly governmental-owned electric companies were established. Thus inexpensive power was a key incentive for economic development. That is, these steps not only created the necessary infrastructure but also controlled electricity prices to provide a stimulus for development to key industries.

This philosophy of subsidizing electricity was the weak cornerstone on which electric utilities were built up in the developing world. Revenues often tended to be insufficient to cover the operating cost of the power plants. The resulting financial deterioration was accelerated by the first and second oil price crises. When import prices for fuels increased by a factor of 4 or more and their denomination in US dollars put an additional burden on the balance of payments, governments in the Third World were no longer able to subsidize electric utilities. The result was a disruption in ability to provide urgently needed additional capacity investments.

Scarce financial resources led to the “discovery” of independent power production, wherein the required investments could be found by attracting private consortia to close the investment gap of the financially weak public power companies. By the end of the 80’s, independent power projects (IPP) were sometimes considered to be the universal remedy to revive the weak power sector in the developing world. However, it has been a painful process to recognize that no private consortium will invest where the risks (political, economic, financial, regulatory and operational) outweigh the reward offered in the form of revenues from the entity purchasing the electricity produced.

Today, a few countries in the developing world, specifically those with highest GDP growth rates in the recent past, are offering conditions attractive enough that large international consortia are being formed to offer electricity on a long term basis. While the situation is far from settled, recent experiences in South-East Asia, Argentina and Chile are showing the evolution of a viable market.

2.1 Character of the Actual Power Market in the Sunbelt

Let’s examine the plant capacities and electricity costs which characterize the emerging IPP market (the larger perspective of the overall market size and potential penetration of renewables will be explored in section 9). Most typical is a demand for base-load cheap electricity supplied by large units. Take, for example, power plant complexes like Paiton II, a 2 x 610 MW coal power station complex in Indonesia, or the large gas-fueled combined cycles with unit sizes of 600 MW and more in Thailand and Malaysia. It appears from these first successful commercial IPPs that the appetite for power is so great that it is the large and more economical base-load plants which are most easily financed, with less attention paid to the regulation and incentives for mid- or peak-load units (which become more important in mature power sectors).

The large and more economical base-load plants are most easily financed compared to smaller mid-load or peak-load systems

The cost structure and competitiveness of different power plant types is illustrated in Figure 2-1. The large range of Levelized Electricity Costs[1] (LEC) for each of the power plant technologies is basically driven by the economies of scale for larger units and the operating strategy, i.e. base-, mid- or peak-load operation. That is, operating at higher capacity factors (or full load hours) reduces the unit cost of the power produced for same capital investment. The figure shows why IPPs are typically large, base-load operated coal or combined cycle configurations, depending on the availability and cost of the associated fuel.

The LECs of power plants strongly depend not only on economies of scale but also on the capacity factor

Large hydro-electric plants, a renewable power source, are of course successful in an internationally competitive market. However, the sites still untapped are diminishing, where this competitive and clean power source can be used. In addition, there are concerns from the investor community about large hydro electric projects when large land areas are inundated.

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[1] The LEC is the annualized life-cycle cost of a kWh produced by a power plant. It is further discussed in. Section 7.

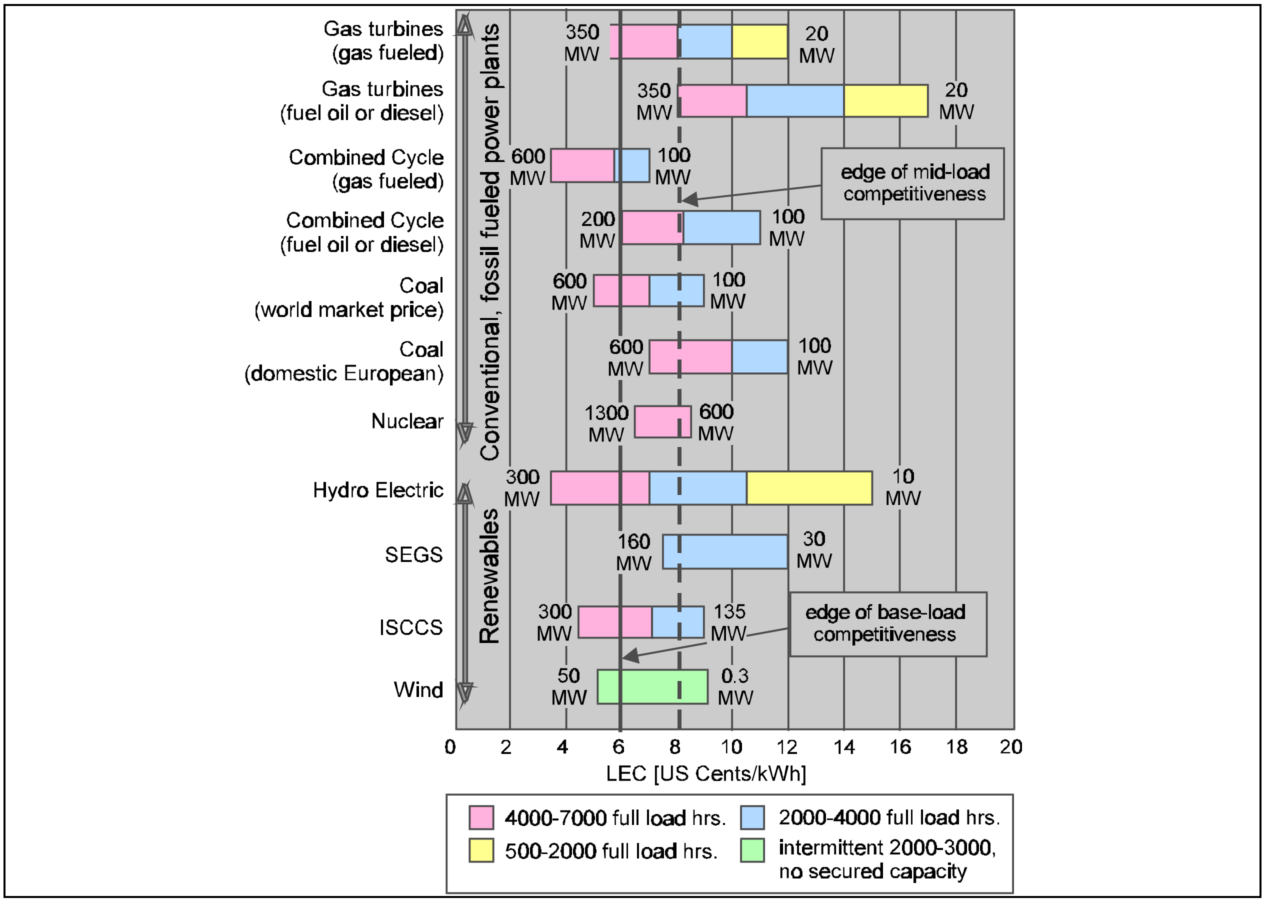

Figure 2-1 Range of LEC for Different Power Plants by Type, Size, Fuel and Utilization

Of the other renewable concepts[2], only base-load operated integrated solar combined cycle systems (ISCCS) are able to compete with large scale fossil-fueled power plants. This will be possible where a cheap gas supply is available in high insolation areas. Promising locations are northern Mexico, northern Morocco, Algeria, Egypt, the Gulf Region of the Arabian Peninsula, Bolivia, northern Argentina and northern Chile.

Although large wind power parks are also able to produce electricity below the edge of base-load competitiveness, their electricity generation is intermittent, or non-dispatchable. Utilities prefer dispatchable sources to meet demand, and once the supply share of wind is on the on the order of 10-15% wind systems may encounter resistance because utilities can face grid voltage control problems. This, in turn, can be expected to lower the compensation for wind-generated power to avoided fuel costs in a highly competitive market.

However, there is another critical consideration in the compensation methods for IPPs. Foreign investors typically require that the compensation be sufficient to account for the potential risks incurred in a project associated with future fluctuations in currency exchange rates, future fuel supply availability and cost, and possible changes in government policy. Since the investors will require a sufficiently attractive return on their equity investment, the compensation for electricity must include these factors and

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[2] Section 3 will briefly describe the principles and types of the direct solar energy power systems., and section 7 will discuss power plant configurations such as ISCCS.

will thus be higher than normally required by a utility installing its own capacity. Hence the available compensation must be significantly higher - on the order of 10% - than the actual levelized electricity cost of an IPP plant indicated in Figure 2-1 because of these risks and investor requirements.

2.2 The Story Behind Solar Power Plant Economics

Solar thermal electric plants are basically conventional thermal power plants with a dual fuel source: fossil fuel plus the radiation energy from the sun. Although the “solar fuel” is free, the solar field itself represents an investment on the order of 45 to 55% of the total solar plant’s investment cost. Thus investment dollars spent today avoid future burning of fossil fuel. If fossil fuel costs are low, which is currently the case , avoided fuel costs provide minimal payoff of the solar field investments.

The implementation of the SEGS projects in California showed that the specific investment cost could be lowered from initial 4,500 USD per kW to less than 3,000 USD per kW. However, the specific investment cost of the latest SEGS unit is still double as high as a comparable fuel-oil fired steam plant, and an ISCCS-plant will cost about 40-60% more than a pure combined cycle system (Figure 2-2).

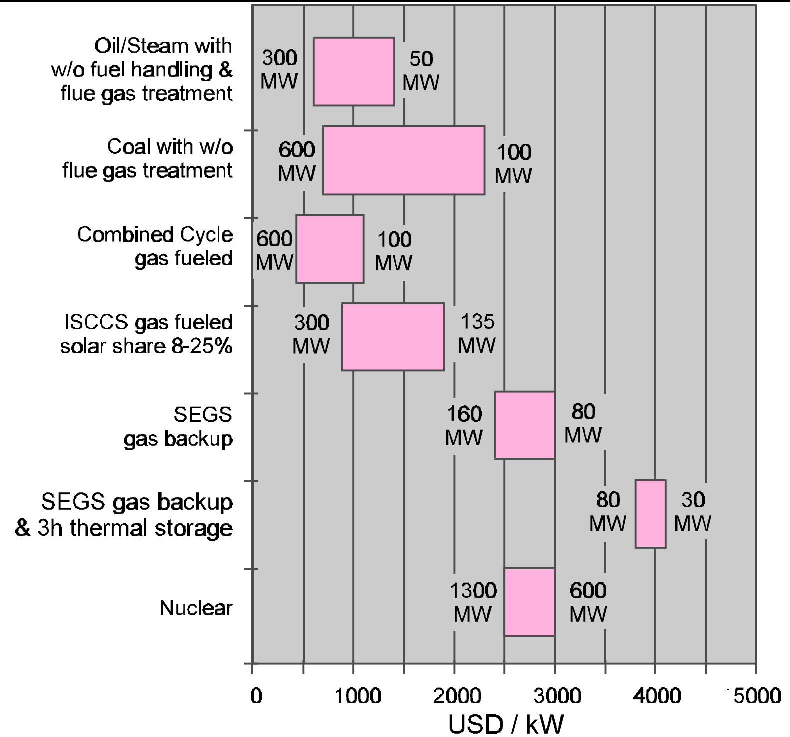

Figure 2-2 Range of Specific Investment Cost for Selected Power Plant Types

On top of this specific investment cost disadvantage, solar thermal power plants are faced with the “capacity factor gap”. Due to the intermittent nature of solar radiation, the “free” solar resource is available about 2,000 to 2,500 full load hours per year, depending on location. This contrasts with fossil-fueled power plants which typically operate 4,000 to 7,000 full load hours per year. As a result, a solar plant operating without fossil assist would have about half the annual output of a comparable fossil plant (and this at a higher investment cost)[3].

While hybridization of a solar plant through the supplementary use of fossil fuel can significantly reduce the cost of electricity, this introduces some conflict with the goals of maximum fuel savings and emission reductions. Another option is the deployment of large thermal storage which, together with a larger solar field, is able to store additional solar energy for three or more full load hours of evening electricity production.

This so-called hybridization of solar thermal plants does not mean that environmental aspects are neglected. On the contrary, with increasing competitiveness of solar thermal power plants and rapid growth into the competitive markets in the Third World, the environmental benefits of fuel saving and emission reductions will be accelerated. However, solar thermal power plants will have the greatest impact only if they are able to grow into the market segments of mid-load to base-load power production based on a small incremental power generation cost compared to fossil fueled power plants. A combination of initial market introduction incentives and leveraging of higher investment cost is needed now in order to later profit from cost reductions by mass production and standardization of solar thermal power plant implementation.[4]

Solar thermal power plants will have the greatest impact only if they are able to grow into the market segments of mid-load to base-load power production

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The Demise of Luz - Lessons from an Unstable Regulatory Environment

In the 80’s, the State of California was the Eldorado for renewable power production. California was the showcase for the rapid development and market introduction of hundreds of megawatts of geothermal, wind, solar thermal and photovoltaic capacity. As a reaction to the second oil price crisis, when the crude oil price rose to nearly 40 USD per barrel, tax incentives were given to private investors and private renewable power generation was allowed to attract the technological development for fossil fuel saving power concepts. California was specifically innovative as the technological development was much more based on a market pull than on a technology push, the concept favored in European R&D support for renewables.

With attractive long term power purchase agreements as well as federal tax incentives, nine solar electric generating systems (SEGS) were erected between 1984 and 1991. 1.2 billion USD were raised, basically from private risk capital investors and, with increasing confidence in the maturity of the technology, from institutional investors. The power purchase agreements for the 3rd to 7th plants had

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[3] It is interesting to note that the capacity factor limitation is also true for wind turbines with typical full load hour ranges of 2,000 to 3,000 hours per year and, more surprisingly, also for the majority of mid-sized hydro-electric plants. However, wind parks, photovoltaic power plants and hydro-electric plants don’t feature the inherent possibility of back-up fuel electricity production available to a solar thermal power plant with a back-up source.

[4] An outline of possible cost reductions is given in section 5.

fixed revenues for energy payments for the first 10 years, i.e., for the avoided fuel cost of the electric utility. These fixed energy payments at an attractive high level reflected expectations in the early 80's that oil and gas prices would remain high. Solar power offered a hedge against possible fuel price escalations. When oil and gas prices rapidly fell in the middle of the 80's and remained at a low level, energy payments were not fixed but were linked to the actual price of natural gas, which decreased from 1981 to 1991 in real terms by nearly 80% (see Figure 2-3).

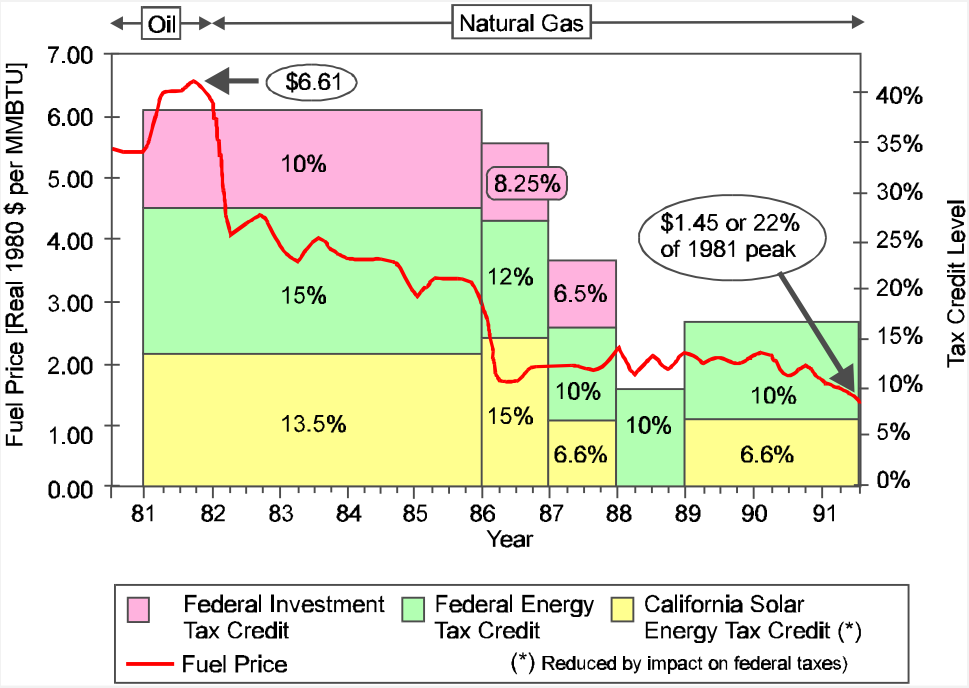

Figure 2-3 Gas Price and Related Energy Payment Decline and Policy Support for Solar Power

Thus Luz, the pioneering company which designed, constructed, financed and operated all the SEGS plants, encountered a rapidly changing energy economic environment after the successful completion of SEGS VII, the last 30 MW unit. When legislation finally allowed for the construction of 80 MW solar power plants (in the early 80's, nobody could imagine solar plant unit sizes beyond 30 MW), tax credits which had specifically attracted private investors to invest in an environmentally responsible technology expired and were subject to annual renewal, if at all. Luz then had to fight year by year for the renewal of tax credits in order to compensate for the revenue decrease caused by the lower energy payments for the first 80 MW projects. Luz' efforts to continue with the implementation of the more cost effective 80 MW solar plants are a lesson on how industry and technology policy effects are caused by a short-sighted tax and energy policies. Late approval to construct and an early end date on the tax subsidy led to significant construction cost overruns in SEGS IX. While Luz still achieved the construction of the plant, the company was financially weakened.

During the 1991 development of the third 80 MW plant, SEGS X, another regulatory issue finally caused the end of the parabolic trough solar power plant success story. The State of California had recognized the greater land requirements for solar plants in comparison to conventional fossil fired power stations, and therefore exempted the solar field part of the plant from the State Property Tax. This exemption expired end of 1990 and was not renewed until May 15, 1991. This additional constraint combined with the December 31, 1991 requirement for inter-connection of the plant to benefit from the available tax credits meant that the tenth SEGS plant had to be constructed in about 7 months. Luz was thus squeezed for the third time to an untenable construction period. Investors lost confidence that the project could be built in time to benefit from the tax credits and withdrew investment commitments. Luz had to file for bankruptcy and was liquidated at the end of 1991. Ironically, in 1992, the US congress recognized the contradictory tax policy and established a more stable tax incentive framework for a period of 5 years. The demise of Luz did not result in closure of the nine SEGS plants. Owned by investor groups, these plants continued to operate well.

The demise of Luz teaches some important lessons. Consistency and stability of tax and energy policies are essential. Specifically for highly capital-intensive new technologies, stable policies are a pre-requisite in an early development stage. The unpredictable changes experienced in this particular case not only exhausted Luz financially but put an additional risk and insecurity on the investors. Another energy policy related issue must surely be questioned: if the long-term strategy is to reduce the dependency on fossil fuels, is it then wise to couple the revenues for renewable electricity to the price for fossil fuels, in this case natural gas? Under this pricing scenario, the price signals from fossil fuels will only attract investment in renewable power when it is too late. For example, with low fossil fuel prices the demand for fossil fuel will increase, which in turn might accelerate the fossil fuel price, in some cases rapidly. The time is then too short to have the back-stop technology in place to react to fossil fuel price escalations.

California was a showcase for a market oriented renewable power introduction but it was also the showcase for short-sighted tax and energy policy considerations. Not only were the positive environmental benefits of the technology not recognized in the available electricity tariffs, but investors were deterred because any investment in renewable power was linked to the uncertain future fossil fuel price development.

Figures

3. Solar Energy Systems

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3. Solar Energy Systems

3.1 The Solar Resource

Of the sun’s rays which pass through the earth’s atmosphere to the ground, a portion is scattered by particles or clouds. The intensity of solar radiation outside the atmosphere is about 1.3 kW/m². Even though only a fraction of this actually hits the earth’s surface, the magnitude of the energy from this source is enormous. Consider, for example, that utilizing only 1% of the earth’s deserts and applying a conversion efficiency of 15% to produce electric energy would develop more electricity than is currently produced worldwide by fossil fuels. This is not practical given the need to distribute the electricity to users around the world, but it does highlight the magnitude of this resource.

Solar radiation is abundant ¾ solar power stations built on the equivalent of only 1% of semi-arid or arid lands could in theory supply the world electricity needs

Technically speaking global radiation, which includes all radiation energy incident on surface, is comprised of a diffuse (scattered) component and a direct normal component (the part coming undisturbed directly from the sun). Figure 3-1 illustrates the definitions of Global, Diffuse and Direct Normal Radiation (DNR).

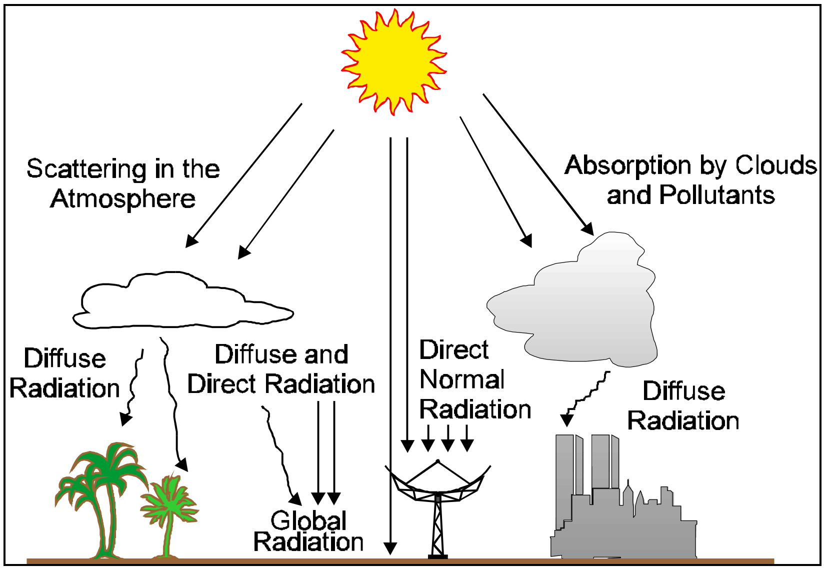

Figure 3-1 Direct Normal, Diffuse and Global Radiation

Because the sun is an intermittent resource, its energy is not available throughout the day and seasonally with the same intensity. The angle of the sun’s rays relative to the earth’s surface changes during the day and with the seasons. The sun is low in the sky in winter, which results in a lower energy flux and causes air temperatures to drop. In summer, the sun is overhead and the energy flux is high. Radiation levels are affected by both weather conditions and the length of the path traveled by rays through the atmosphere. Figure 3-2 shows these effects by illustrating actual data for direct normal radiation which is used by concentrating solar electric systems in the Mojave Desert of California.

Direct normal radiation is affected by both weather conditions and the length of the path traveled by the sun's rays through the atmosphere

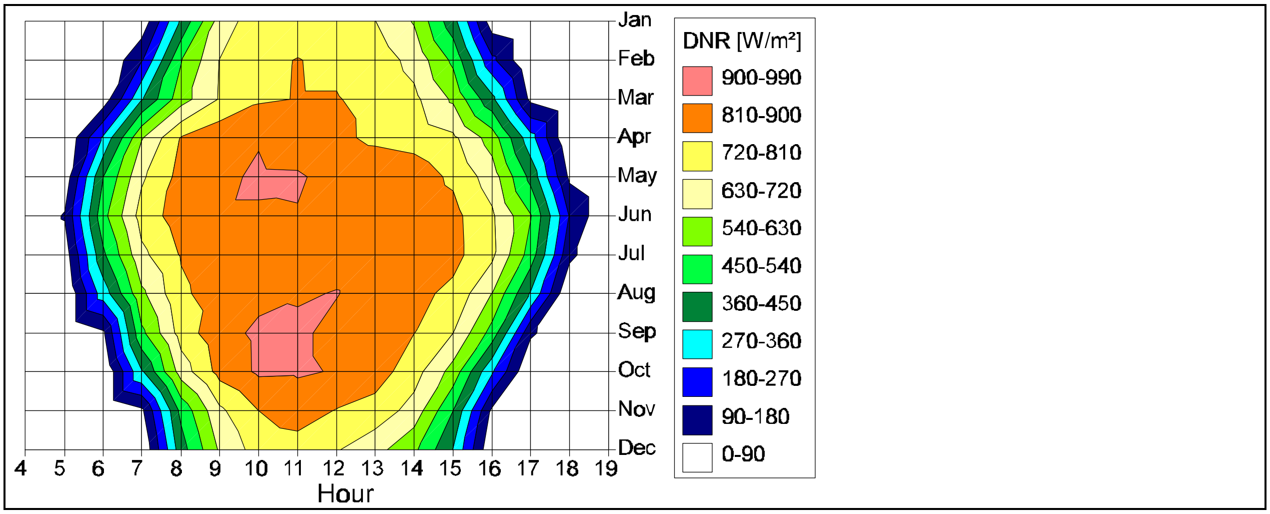

Figure 3-2 Typical Daily and Seasonal Distribution of Average Direct Normal Radiation in the Mojave Desert

There are many ways to exploit the sun's energy. *Primary* systems absorb the rays of the sun to produce heat or electricity, while *secondary* systems take advantage of the wind, moving water or vegetation, all of which derive from the sun's energy. This report focuses on primary solar resources, i.e., solar thermal and photovoltaic systems, and will not treat secondary renewable energy resources such as wind, hydro and biomass. Primary *solar thermal* systems can collect heat and use it for household applications (heating and warm water) or industrial process heat in a temperature range of 90-280°C for steam generation or, e.g., desalination. Furthermore, they can collect the solar energy as heat and transform it into electricity in a thermal power conversion system. However, there is a third primary system, fundamentally different from the first two, which directly converts sunlight into electricity using the *photovoltaic* effect. In all the primary systems, the sun's radiation may be either absorbed in a flat plate collector or concentrated optically using mirrors or lenses. The selection of an appropriate technology depends on the application, energy demand, location, and meteorological conditions. Meteorological and sun angle effects have a greater impact on concentrating collectors, which utilize only the direct rays of the sun, than on flat plate collectors which utilize both the diffuse and direct components.

Primary renewable energy systems absorb the rays of the sun to produce heat or electricity, while secondary systems take advantage of the wind, moving water or vegetation, all of which derive from the sun's energy

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Solar Power Plant Performance Calculation

The combined effect of sun angles and weather affecting the daily and seasonal production of solar electrical power from a SEGS system is shown Figure 3-3. The proper treatment of these effects plus specific power plant operating restrictions requires the help of computers in order to calculate the electrical output of solar power plants. The primary tool in this calculation is the plant Performance Model.

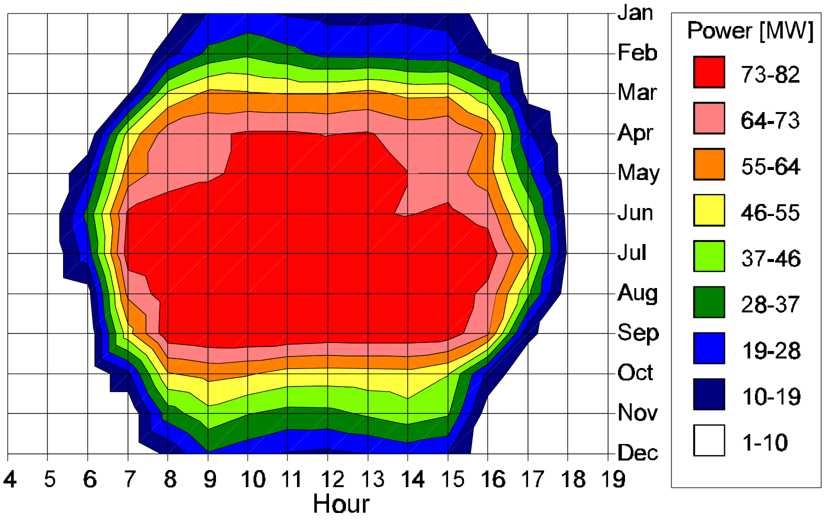

Figure 3-3 Typical Average Solar Electricity Production of SEGS

3.2 Solar Thermal Electric Power

Concentrating solar thermal collectors are predominantly used to generate electricity. Various system designs differ in the way they concentrate and collect sunlight, but the final step of generating electricity is identical to conventional (fossil fired) power plants, that is, a heat engine is used to convert thermal to electric energy. This principle is always the same: a working fluid is compressed, heated and eventually evaporated (by either solar or conventional means), expanded (in expanding, the fluid drives an electric generator via turbine blades or pistons); and, finally, the fluid is condensed again. Figure 3-4 illustrates this general process.

The solar system has the task of concentrating sunlight and transforming it into heat, which then is used in the heat engine. Put simply, a solar thermal power plant is a conventional power block using solar energy as its primary heat source. As will be shown later in this report, a fossil fuel heat source can be integrated with the solar system.

A solar thermal power plant is a conventional power block using solar energy as its primary heat source. Integration with an alternate fossil-fuel heat source is possible.

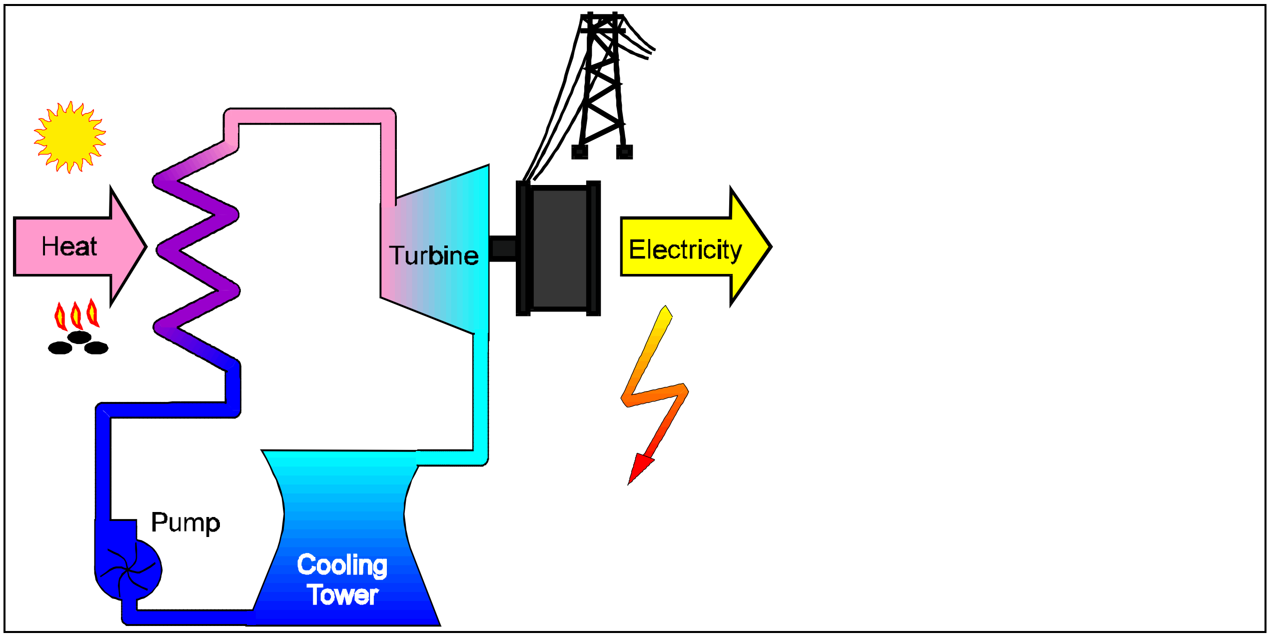

Figure 3-4 Principle of Converting Solar and Fossil Heat into Electricity

3.2.1 Parabolic Troughs

Parabolic troughs consist of long parallel rows of identical concentrator modules - typically glass mirrors - that are curved in only one dimension, forming troughs. Tracking the sun from east to west while rotating on a north-south axis, the trough focuses the sun’s energy on a pipe located along it’s focal line (Figure 3-5). Troughs can also rotate on an east-west axis but such systems normally yield less annual energy; however, the output tends to be seasonally more uniform. A heat transfer fluid, typically oil at temperatures up to 400°C, is circulated through the pipes and then pumped to a central power block area, where it passes through a heat exchanger. The oil’s heat is then passed to a working fluid, such as water or steam, which is used in turn to drive a conventional turbine generator. Several commercial units with sizes up to 80 MW_e were put into operation with peak net electric efficiencies of 23%.

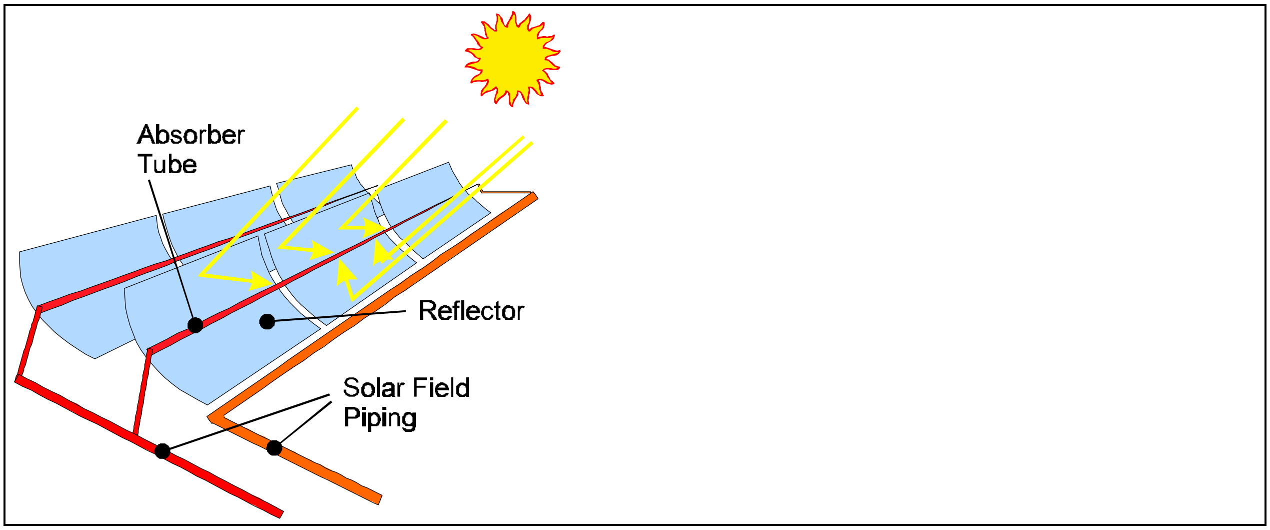

Figure 3-5 Trough Principle

3.2.2 Central Receivers

Solar central receivers, shown in Figure 3-6 and also known as “power towers”, consist of a fixed receiver mounted on a tower surrounded by a large array of mirrors, or heliostats. The heliostats track the sun on two axes and reflect its rays onto the receiver, which absorbs the heat. Within the receiver, a fluid - water, air, liquid metal and molten salt have been tested - absorbs the receiver’s heat energy and is then transported from the receiver to a turbine generator. Several test units have been built with capacities of 0.5 to 10 MW_e.

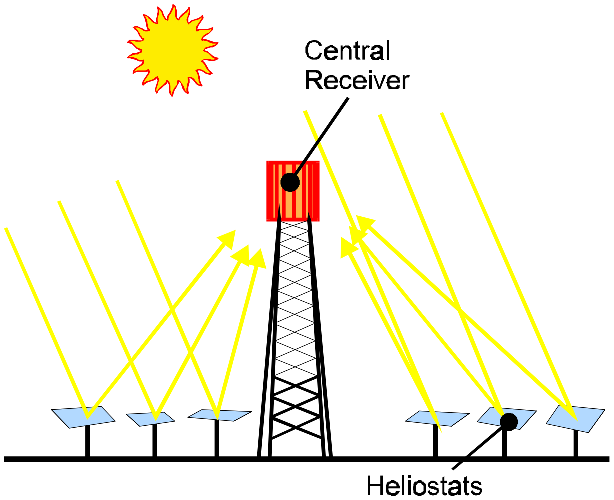

Figure 3-6 Tower Principle

3.2.3 Parabolic Dishes

Parabolic dish systems (Figure 3-7) consist of a parabolic-shaped point focus concentrator in the form of a dish that reflects solar radiation onto a receiver mounted at the focal point. These concentrators are mounted on a structure with a two-axis tracking system to follow the sun. The collected heat is typically utilized directly by a heat engine mounted on the receiver moving with the dish structure. Stirling and Brayton cycle engines are currently favored for power conversion. Projects of modular systems have been realized with total capacities up to 5 MW_e. The modules have maximum sizes of 50 kW_e and have achieved peak efficiencies up to 30% net.

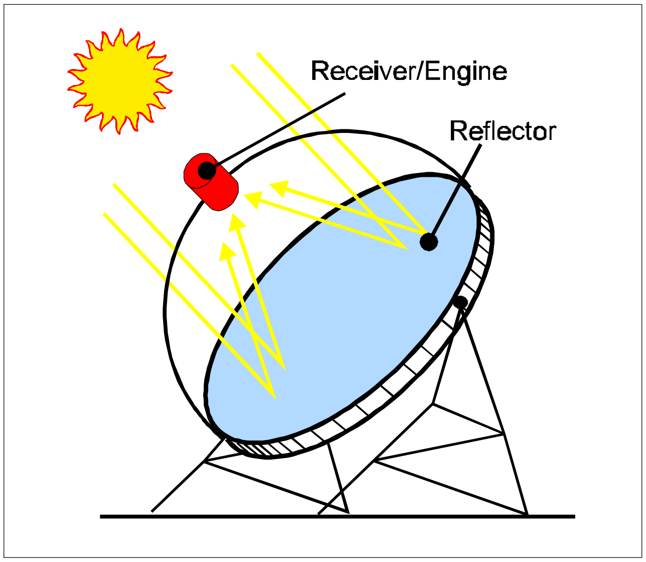

Figure 3-7 Dish Principle

3.3 Comparison of Major Solar Thermal Electric Technologies

Each solar thermal option has its own characteristics, advantages and disadvantages. Table 3-1 contrasts the three choices with respect to typical applications, current state of development and special features.

Each solar thermal option has its own characteristics, advantages and disadvantages

	Tower	**Dish**	**Trough**
Applications	grid connected plants, high temperature process heat	stand alone applications or small power systems	grid connected plants, process heat
Status	test and demo units; maximum 10 MW_e; commercial status about 1999; designs for integration with combined cycles.	test and demo units: stand alone systems $\leq$ 50 kW_e and farms $\leq$ 5 MW_e; commercial status about 1998.	commercial size 80 MW_e units, total 354 MW_e operating; designs for integration with combined cycles
Advantages	good long-term perspective for high efficiencies and storage through high temperatures, hybrid operation possible.	very high conversion efficiencies, modularity, hybrid operation in development	commercially available, with 4500 GWh operational experience, hybrid concept proven, storage capability
Disadvantages	capital cost projections not yet proven; heliostats require very high tracking accuracy; air receiver has reached prototype stage; promising salt receiver system not yet proven	fossil back-up not yet proven, storage a problem, high cost an issue, development has reached prototype stage	lower temperatures restrict output to moderate steam qualities through temperature limits of oil

Table 3-1 Comparison of Major Solar Thermal Concentrating Technologies

3.4 Other, Non-concentrating Solar Thermal Electric Technologies

Trough, tower and dish systems utilize the sun’s heat by concentrating the radiation, and therefore they can only use the parallel rays (DNR) that come directly from the sun, unmarred by clouds, dirt or mist. Other solar thermal electric systems, namely include solar ponds and solar chimneys, are able to utilize global radiation, comprising both the direct and diffuse parts of sunlight.

3.4.1 Solar Ponds

In a solar pond, salt is used to create a dense brine on the bottom of a shallow body of water, while fresh water is supplied at the surface. As the sun’s rays penetrate the top layer, they are absorbed in the lower layers, heating the brine at the pond bottom. As the hot brine is denser than the less salty water above, it cannot rise and heat losses to the atmosphere are inhibited. It is this temperature gradient between the deep hot layer and the upper cooler layers which allow power to be produced. The heat can be extracted by passing the brine through a heat exchanger to warm the working fluid of a heat engine, with the cooler water from the top of the pond used for the cycle’s condensing water, as shown schematically in Figure 3-8. Its advantages are its simple design and inherent storage capability. On the other hand, solar ponds have a very low solar-to-electric efficiency, limited siting possibilities, high water and salt requirements and large land area needs. Test units of 5 MW_e have achieved 0.9% solar-to-electric net annual efficiency.

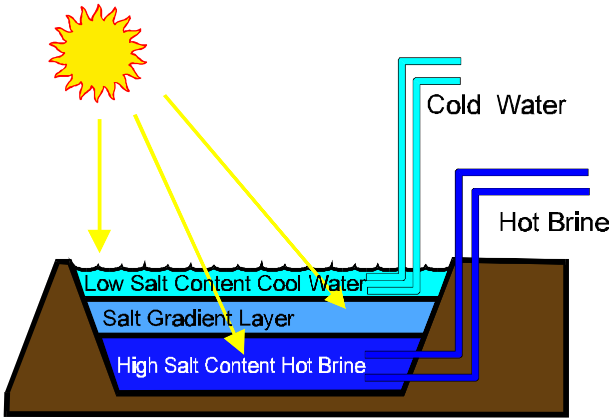

Figure 3-8 Solar Pond Principle

3.4.2 Solar Chimney

The solar chimney consists of a large area of above-ground translucent panes, a vertical pipe, the chimney, and a wind turbine. The non-concentrated solar radiation heats up the air underneath the panes, which becomes less dense, providing the driving force for the air to move upward through the chimney. The energy is extracted from the air stream through a wind turbine located at the neck of the vertical pipe, (see Figure 3-9). Test units of 50 kW_e have been built with a solar-to-electric net annual efficiency of 0.05%.

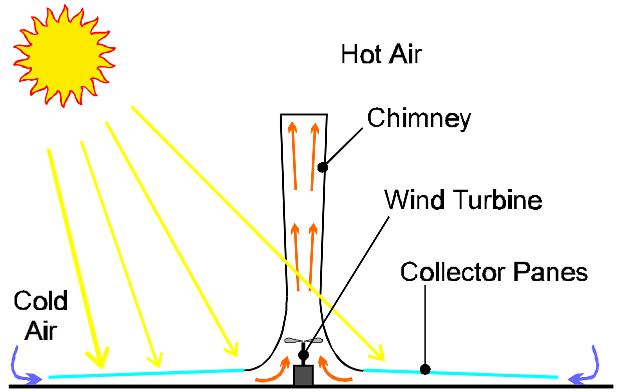

Figure 3-9 Solar Chimney Principle

The low efficiencies of these non-concentrating systems are somewhat balanced by the rather low investment cost per m² of aperture.

3.5 Photovoltaics

Photovoltaic (PV) devices, commonly called “solar cells”, convert sunlight directly into electricity using a method that differs fundamentally from the heat engines used in the solar thermal modes of electricity generation. The principle exploits the photovoltaic effect whereby photons (light), striking a specially designed solar cell, force the movement of electrons. The intermediate step of transforming radiation into heat is omitted. PV-systems are becoming widespread in low-power applications as diverse as pocket calculators, remote communication and lighting systems, and architectural facades in buildings. Utility-scale plants are also possible and proposed projects for such systems are becoming more prevalent. Due to the high cell cost PV systems thus far have tended to be limited to applications in the range from milliwatts to kilowatts; but in certain remote applications PV with battery storage is an economically viable power source. Figure 3-10 shows a grid connected PV application for households.

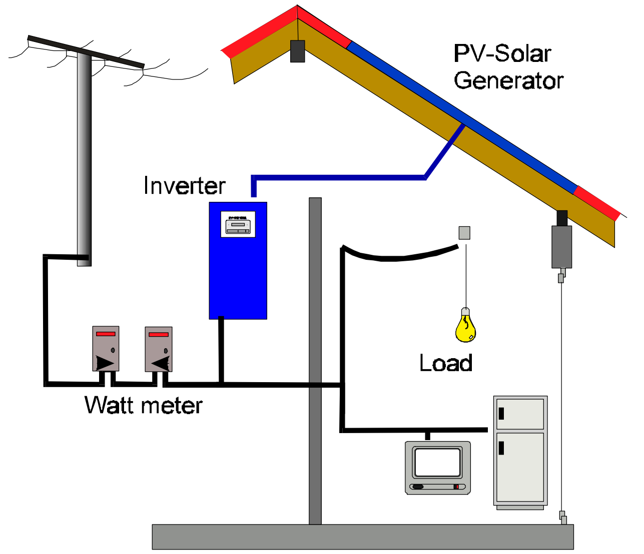

Figure 3-10 Grid Connected PV-generator for a Household

Photovoltaic devices or “solar cells” convert sunlight directly into electricity using a method that differs fundamentally from solar-driven heat engines

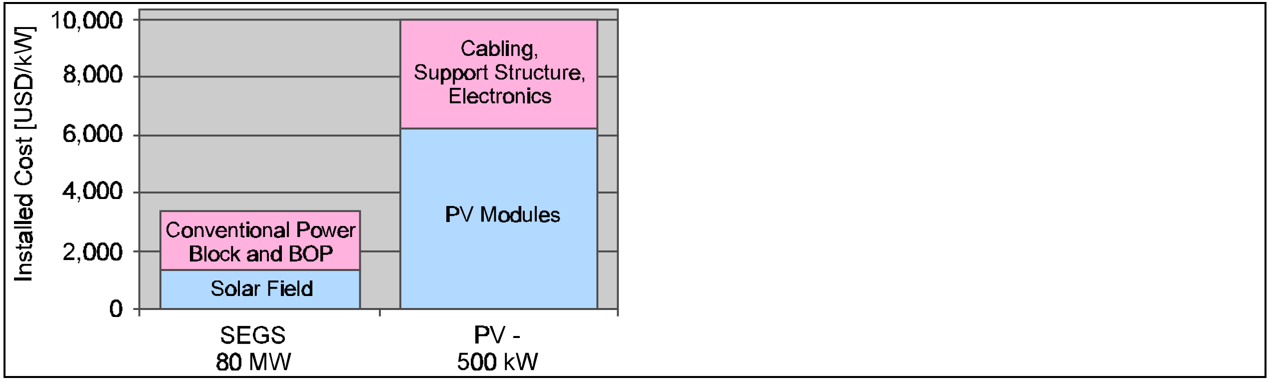

Figure 3-11 Specific Investment Cost

The cost per kW installed of PV compared to solar thermal power is relatively high at present, as illustrated in Figure 3-11. Future costs will largely depend on the ability to lower PV cell and module costs with mass production, though balance-of-system costs constitute about half of the total costs and will also need reduction.

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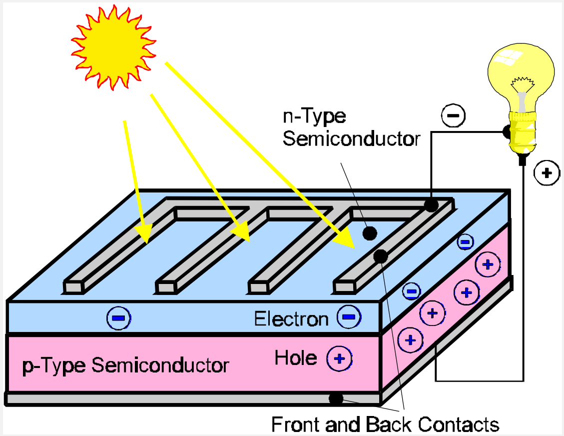

Figure 3-12 PV-Principle

PV principle: The body of a solar cell consists of two layers of semiconductor material (e.g. silicon) doped with foreign atoms (e.g. boron and phosphorus) to produce different electrical properties in each layer. An electric field forms at the junction of these two layers. When light strikes the solar cell, its energy generates unbounded charge carriers that are separated by the electric field, as in Figure 3-12. When an external circuit is connected, electric current flows which is proportional to the incident energy. There are different types of commercially available cells: single-crystalline (<16% efficiency but high cost), polycrystalline (<14% efficiency), and amorphous (the manufacturing process promises great cost reductions, though performance is currently low at about 5%).

3.6 Operating Experience

From the various solar thermal technologies, the solar trough is the only one that reached commercial, utility-scale electricity production. Projects employing other technologies at or close to this scale have predominantly been built as test facilities and demonstration plants, with most of the capacity presently decommissioned. Figure 3-13 shows the cumulative operating experience of different systems in MWh_e. While only a small number of PV systems of a MW-scale have operated, the very high number of kW-scale and smaller system adds to a respectable cumulative total.

Only solar parabolic trough power systems have currently achieved commercial, utility-scale electricity production

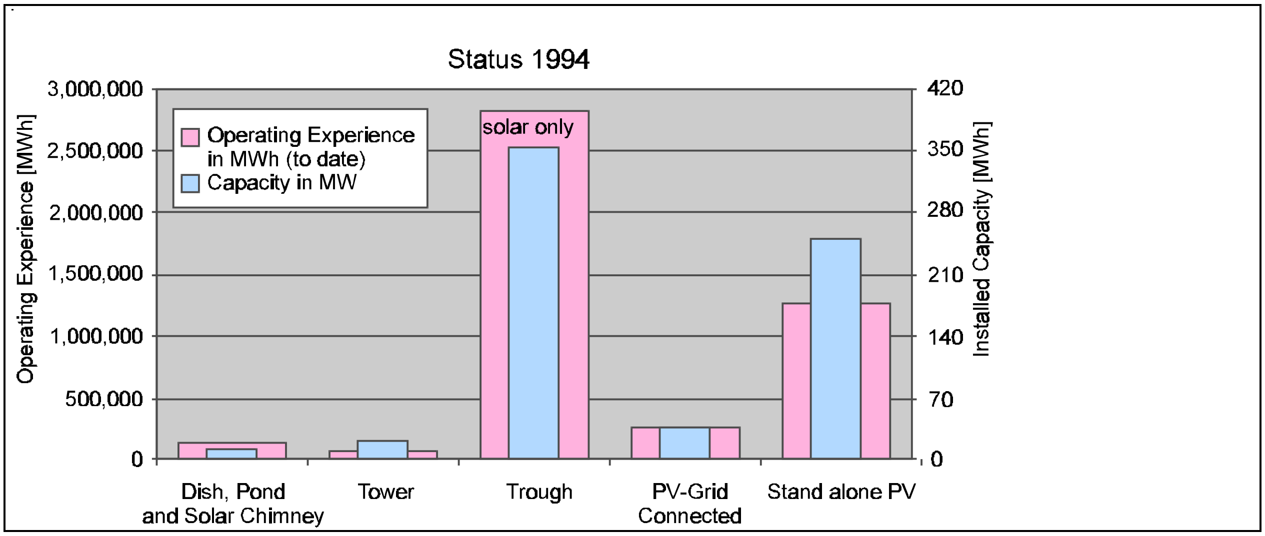

Figure 3-13 Operating Experience of Various Solar Technologies

Figures