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Solar Thermal Energy: The Forgotten Energy Source

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1. Introduction

Much has been written recently about alternative energy (1). Concern has centered on the need to reduce reliance on imported oil and, more recently, on gas imports – as well as on the need to reduce global warming caused by fossil fuels (2). In these articles, solar energy is never considered for a dominant role, and it receives only a tiny allocation within the total DOE budget. This paper explains how solar thermal energy, together with nuclear energy, can become the major energy source at an affordable price (3, 4). We also show that solar thermal energy properly designed can provide an anchor for an advanced concept of the national grid which can be integrated with solar cells, wind and nuclear energy. Another important advantage of solar thermal energy is the ability to co-generate electricity and desalinated water.

Though a proven technology which has been operating in California since 1985, solar thermal energy is generally assumed to be so expensive, it cannot become competitive with conventional coal power plants (5). Although at base load, solar thermal energy is not yet competitive with nuclear power or with the new coal power plants, for intermediate electricity loads (8:00 am to 9:00 pm; 50% of our electricity needs), it competes with or is cheaper than any available new plant, including conventional coal power plants with a scrubber. Properly designed it can supply a strongly variable electricity output with instantaneous response for peak (10%) and variable loads (the most urgent need of the grid) for several hours duration, cheaper than any other

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technology presently available (aside from hydroelectric). These conclusions are based on a conservative evaluation of proven technologies made by Sargent and Lundy (4). When many plants are built, mass production and experience can reduce costs for base loads to the level of other clean technologies. Even now, solar thermal power plants designed for intermediate and strongly variable loads are competitive and, except for the first demonstration plants, will not require government subsidies. Solar thermal energy only requires the initial support that nuclear energy and the new clean coal technology needed to get started.

Our society needs to reduce greenhouse emissions and faces uncertain reserves of oil, gas and coal (2). Therefore, we must switch slowly from the use of fossil fuels to solar and nuclear electricity. A gradual switch to a non-fossil electric economy could prevent the potential catastrophes predicted in Ref. 6. It would also reduce greenhouse emissions and preserve fossil fuels for uses for which there are no substitutes, e.g., aviation fuel and raw materials for petrochemicals. Solar thermal energy could also play a major role towards a gradual reduction in US dependence on fossil fuels from an unstable Middle East.

Electricity can replace fossil fuels for most residential uses and partially replace gasoline and diesel for transportation. But first, the national grid would have to be enlarged so that the electricity needed to meet the growing demand for energy could be distributed from the Southwest where it is generated from solar thermal energy. Were the US able to develop affordable solar energy on a large scale, the impact on the world economy would be tremendous because other countries such as China, Australia, and parts of Africa also have large desert areas suitable for generating solar thermal energy. Where deserts are located near the ocean, solar thermal electricity production can be coupled with water desalination, thereby reducing the costs of both processes. Thus, renewable energy could be provided for the developing countries on a large scale without fear that it will be used to produce nuclear weapons.

Solar thermal electricity is already cheaper than electricity produced in a coal power plant with CO₂ sequestration, therefore it could become a major factor in any plans to reduce greenhouse emissions. This paper argues that, if implemented on a large scale, solar thermal energy can supply 50 to 70% of our energy needs at competitive rates without requiring further development.

2. Overview of the Available Solar Technologies

Two solar technologies can provide electric power. One is based on solar collectors that supply heat to a conventional steam-based electricity plant (4). The second is based on solar cells (7), which convert sunlight to electricity directly. Both solar technologies share the same problem; sun only shines during part of the day, and the intensity changes with the time of the day and the weather. Variations in the supply of solar intensity necessitate a capacity for energy storage and a back-up source. In the following sections we review the state of these technologies.

2.1 Solar Thermal

Arnold Goldman (3) developed parabolic solar collectors that store heat in heat transfer fluid at high temperatures rather than in pressurized water. Ref. 8 gives a simplified overview of this innovative technology. Figure 1 presents a schematic diagram, and more detailed descriptions of existing plants are given in Refs. 9-12. Central to the plant design is a large set of concentrating solar collectors, the most costly part. These consist of simple, and robust parabolic concentrators with two-dimensional tracking (called trough collectors, see Figure 2); other concentrating collectors could be substituted. The collectors heat a heat transfer fluid that is stable between 750-800 °F (either a poly-aromatic Dowtherm A, a silicon-based fluid, or a molten salt) as it flows through a set of pipes. The hot heat transfer fluid is pumped into an insulated underground storage tank and then through a steam generator as needed. Storage tanks with cold fluids build up during the night. During the day the fluid is fed back to the solar collectors and then, to the

hot fluid storage tanks. Added as backup for the few days when there is no sun, the plant includes an auxiliary furnace, able to operate with natural gas or oil. This capability is critical in the design of any solar energy plant. Our own design modifies the original, by specifying an over-sized steam power plant that can accommodate to large fluctuations in demand. This increases the investment slightly (< 30% for a plant over-sized by a factor of 3) and has a small impact on thermal efficiency.

Only hydroelectric plants can rival solar thermal power plants for flexibility in meeting highly variable electricity demands quickly, efficiently and at a moderate cost increment. All other available technologies require an increase in capacity proportional to the variability (as explained in §3). Wind and solar cells require storage, which, in any form, is expensive and has an efficiency below 80%. This flexibility gives solar thermal energy a significant cost advantage over all other clean technologies. These advantages are the focus of this paper, but they have been overlooked by previous studies (4, 5).

In the 1980s, Goldman founded Luz, a company that built 9 solar thermal energy units in California, for a total of 354 MW, that are still operating today (3). These plants were economical when a 50% tax break was given to solar energy. To obtain the contract the company guaranteed - and delivered - 12 hours of constant electricity each day. While the tax break made Luz competitive, it lacked the Government support and the internal commitment that allowed utility-based nuclear plants to develop in the 1950s. When tax losses to local and national governments became large, Luz's tax credits were withdrawn and Luz went into bankruptcy (3). This was a serious setback for solar energy. As ABB had already agreed to partner with Luz, the design, manufacturing, and construction capabilities of a major energy company could have allowed the solar thermal enterprise to succeed. Only a few solar thermal plants have been built

since Luz collapsed. Had the tax credits continued, the US may have had affordable, large-scale solar electricity today.

The Luz design requires improvement and needs to be adapted to mass production, but the feasibility of the technology on which it is based is irrefutable. There have been several cost and operational analyses (4, 11, 12). Ours is based on a comprehensive study by Sargent and Lundy for DOE (4) on the status of the technology and the cost of a large, updated Luz-type plant.

The plants originally built by Luz, as well as the plants proposed in ref. 4 and 13, do not utilize fully the main advantage of coupling solar thermal energy with a storage capability: an increase in the value of the technology due to its ability to supply variable energy with only a small incremental investment cost. It becomes much easier to argue for the introduction of solar thermal plants if we recognize the very large-scale niche for electric energy they can fill.

Sandia Labs has modified the Luz concept with a solar tower. Their design has a higher thermal efficiency per area of collector, but a lower efficiency per total land area, requiring about double the total area per capacity installed. Solar tower technology is not discussed in this paper, as it has not been proven on a large scale over sufficient time. However, the results apply to it as well. Another solar thermal technology has been developed (www.stirlingenergy.com), but also not yet proven on a large scale. It is based on Stirling engines coupled with a concentrating dish. As the only way to provide for storage is batteries, it shares the same problem with solar cells, they are not suitable for the main purpose of this paper to evaluate solar energy as the main energy source for the future.

2.2 Solar Cells

The solar cells receive attention and support today as they are of greater scientific interest and so, have caught the attention of a large group of researchers (1), however, they lack a suitable storage technology and thus, are less promising as a solution to our energy problems. A process

for energy storage frequently cited and promoted by DOE is the conversion of electricity to H₂, then back again (14). The potential achievable efficiency of such conversions is only about 43%, but, this would increase the size of the panel required by a factor of 2 or 3. Thus, the cost of storing electricity as H₂ would probably quadruple the cost of generating electricity from a solar panel directly.

Without storage, solar electricity must be fed directly into the grid. Unlike wind, the variations in solar intensity are highly correlated in time, requiring a controllable backup energy source to take care of variations in supply to compensate for days that are not sunny. The cost of such a backup plant would have to be added to the cost of the electricity. All these measures can be taken in solar thermal plants at a small cost.

DOE has proposed to reduce the high cost of electricity from solar cells by installing solar panels on the roofs of individual homes, apartment houses and office buildings (1). Each entity would be connected directly to the grid. When needs exceed the capacity of the panels, electricity would be obtained from the grid, and excess electricity would be exported back to the grid. Thus, the user would save the distribution costs (3-5 cent/kWh). The total potential of this concept for supplying electricity on a large scale is limited to a fraction of present residential and office consumption. Whereas, we are here interested in a technology that can supply, in the long-term future, the major fraction of our total energy needs. There are two other problems. Distribution cost is a function of maximum capacity and independent of use. Second it does not solve the problem that the amount of uncontrollable variable electricity inputs the grid can receive is limited. We will later show how solar thermal energy could be used to compensate for variable inputs by providing storage to the grid.

3. Supplying Variable Electricity Loads

Only about 40% of our electricity requirements are steady (base load, see Table 3 and ref. 3). Our entire output from nuclear energy is used in this role at present. The intermediate load, 50% of consumption, occurs between 8 am and 9 pm on weekdays. The remaining 10% are peak loads, which vary widely with the season and time of day and can cause blackouts. This is a strong oversimplification since significant variations in load occur throughout the entire day, especially during the intermediate periods.

Prior to 1992, utilities were guaranteed a return on their investment, so it became profitable to over-invest. To utilize excess capacity for controlling variable loads, a power plant must operate continuously at its lowest feasible output. The steam power plants of the 1960s, which were built with a guarantee of return on investment, had excess capacity and were designed with a minimum turn-down ratio of 8 (the ratio between its standard rated capacity and the minimum capacity at which it can operate efficiently). In 1992 a new law removed the guaranteed return on investment. Due to changes in the economy, since the middle seventies, it was no longer economically feasible for utilities to add a large excess capacity. New technologies based on gas turbines were introduced to meet new demand for peak or intermediate loads. However, all technologies based on gas turbines, including the new clean coal power plants, have a turn-down ratio of 1.25, and are not suitable for fast following, and therefore there is a need to add to the grid new capacity with a large turn-down ratio.

For supplying intermediate and variable loads, solar thermal energy has a unique advantage over either clean coal or nuclear energy. Supplying 1 GW for 2 hours, or even for only 1 hour a day requires a 1 GW power plant even if the average demand is less than 0.1 GW. By comparison, the collectors of a solar thermal plant could be built for average need only (0.1 GW). Only the boiler and the turbines, which represent about 14% of the total investment cost (4), would have to be built for 1 GW. The hot heat transfer fluid can be regarded as a “storable fuel” for the

steam power plant, whereas, in a clean coal power plant with a gasifier, the clean fuel is the product of the gasifier and it is not storable. At present all technology used for fast load following is solely based on steam power plants. In gas turbines load changes larger than 20% cause a significant decrease in thermal efficiency and, unlike a steam plant, are hard to operate at low loads. Thus, the new clean coal power plants are not designed for large, sudden load changes or for providing excess controllable capacity. Although it is conceptually possible, US nuclear plants have never operated this way (they operate for base load), perhaps, because costs would increase proportionally. Present nuclear power plants have no storable intermediate, though by using a liquid metal as a heat transfer medium they could be designed similarly. As a result, the US no longer has a large overcapacity, and to ensure proper functioning, the grid urgently requires variable electricity that is instantaneously controllable. Solar thermal energy is uniquely capable of addressing this need. Should wind energy or solar cells become more extensively used, this urgency would increase as their output is not controllable and can have strong variations which require a quick and reliable backup response.

4. Estimated Costs for Solar Thermal Energy and Other Technologies

As mentioned above, our cost estimate is based on the Sargent and Lundy report on solar thermal energy (4). It evaluates the Luz technology and its performance based on the plants built in the US, developments at DOE, and other related technology. Their cost estimates for solar power plants with trough technology (4), are summarized in Table 4. We use their near term (year 2004) estimate based on a 50 MW plant and slightly adjusted for a bigger size, 400 MW, in a very conservative way (see comment on Table 5). Table 4 indicates that there is a strong potential for further cost reductions (4), and we agree. These reductions are mainly achieved by design improvements. If the US becomes serious about solar energy, trough collectors with a modular design (about 70% of the total plant cost), could be mass produced, thus lowering the

cost of solar thermal plants by a factor of three to four and they would become competitive with all clean power plants. It is important, therefore, that demonstration plants should use a mechanical design that lends itself to mass production and that the collectors should be designed such for easy shipment, assembly, and service by labor with minimal skills.

The Sargent and Lundy analyses (4) are based on proven technology using conservative estimates for the impact of plant size. These estimates apply to an intermediate load power plant (\cong 14 hours a day: 4900 kWh a year / 365 days a year / kW capacity). Using the breakdown of the costs from the Sargent and Lundy report, we can estimate costs of increasing the steam power plant by a factor of three, without changing anything else. This increases the total costs by about 20% (includes savings for the larger scale). In practice each utility would actually choose a specific design that meets its overall load pattern, but the numbers we use bracket the cost of such plants.

The estimate provided in Table 4 for the year 2020 does not depend on future research achievements, but only, on larger size and technical improvements gained from experience. Such cost reductions occur in all new technologies. For example, even though the technology remained essentially the same, the cost of LNG plants and shipping came down by a factor of two in the last 10 years solely because of size and technical improvements (12). Although we believe that with mass production the cost of the collectors could be lowered much sooner, we base all our conclusions on conservative estimates of current construction costs. In Tables 5 and 6 this estimate is compared with published estimates for clean coal, nuclear and solar cells. Table 5 compares the cost per kWh with full utilization of the plant, whereas Table 6 is for intermediate loads.

We must first explain how the numbers for competing technologies were derived. The cost of clean coal, with and without CO₂ sequestration, is from an EPRI report (15), but the substantial

cost of the ultimate sequestration of the CO₂ (16), which strongly varies with the location of the plant, is not included.

It is more difficult to estimate the cost of a nuclear plant reliably as no nuclear plants have been built in the US in the last 20 years. Proposals for the new safer power plants that have been bid but not built have a range from \$1500 to \$2500 per kWh installed, but no utility seems to be ready to build one without a large government loan, guarantees, and subsidies. In our estimates (17) we use \$2200/kW although the exact figure is not critical to our analysis. Estimates for solar cells are from DOE (18).

In Table 5 we estimate costs for base loads solar thermal plants designed to operate only 15 hours a day, which is close to intermediate load (13 hours a day), the only case of present interest. The cost per kWh slightly increases for base load (4), as it requires more storage. We note that the relation between the investment cost per kW capacity and the cost per kWh is different for the different technologies due to different fuel and maintenance, which, for solar thermal, are low. For solar thermal we use the base case in Ref. 4 and give detailed cost calculations in Table 7. The cost per kWh for the other technologies is taken from the references cited.

4.1 Comparison of Costs

In Table 5 the various technologies are compared in terms of: investment cost per kW installed, yearly kWh generated, and cost estimates per kWh. We note that solar thermal electricity has very little chance of competing with conventional coal power plant equipped with scrubbers (0.045 \$/kWh) and certainly not with old, paid-off power plants that lack scrubbers. Here, we agree with the conclusion in Ref. 13. For base load, solar thermal energy also cannot compete with “clean” coal power plants based on entrained bed gasifiers, or with nuclear energy, although it might compete in the future. Even now, however, solar thermal is already significantly cheaper

for base power than clean coal followed by CO₂ sequestration, if the cost of ultimate CO₂ sequestration and pipelining are included. This is a very important conclusion for any plans to reduce greenhouse emissions.

For intermediate loads, however, solar thermal energy is already competitive with – or competes favorably - the new clean coal power plants equipped with scrubbers and with nuclear energy. Since at least half of our electricity needs is for intermediate electricity loads this is a very important point. As Table 8 demonstrates clearly, even at present prices, solar thermal offers a large advantage over all new power plants, even conventional coal power plants with a scrubber, for supplying instantaneously controllable electricity for a wide range of loads, an increasingly important problem for the grid. If wind energy becomes a substantial factor, or if solar cells become radically cheaper, solar thermal plants could provide the needed storage capacity they lack for supplying variable energy on a much larger scale. Therefore, the first solar thermal plants should be built for intermediate loads and controllable energy. Each utility can have them designed to specific local needs. Such plants could become an important tool for the ability to manage the grid.

Today, solar cells are more expensive than solar thermal plants by a factor of three (19), but they merit further study because they can be used for many special purposes; furthermore, we will show later that if research could drastically reduce their cost, their lack of storage could be compensated for by properly designed solar thermal energy in an advanced grid. The cost estimates given here are for solar thermal power plants with water-cooling. One can find locations in the desert with water nearby sufficient for the first 50 to 100 GW. It is unlikely that a desert water source would be sufficient for an output of 1000 to 2000 GW total electricity, and this could cause a local climate change. Air-cooling is an available technology that can be used to solve this problem. Since desert temperatures can reach 120 °F, steam power plants can be

modified with back-pressure turbines (an available technology) to increase the condensation temperature to over 212 °F in order to create a natural draft. As this modification would lower efficiency by 10%, the total investment cost would increase proportionally. Once the first such 50-100 GW solar thermal power plants have been built, the electricity price would be less than \$0.06 / kWh.

5. Combined Production of Electricity and Desalinated Water.

A detailed discussion of the cogeneration of desalinated water and electricity in a steam power plant is beyond the scope of this paper, but it is an available technology (20, 21). For any steam power plant, cogeneration could fill a great need for water, not only in the US, but also throughout the world, especially in developing countries. In the Mediterranean area, where many deserts are located close to the ocean, the main interest in solar thermal power is for this purpose. In modern desalination plants, which operate at low pressures, investment is strongly dependent on scale; for large-scale production, the major cost of the water is the fuel. Here cogeneration can have a big impact.

A steam power plant with a back pressure turbine, which condenses steam at 240 °F, reduces the power output by about 12%, and produces 5 lb of steam per kWh at a cost of \$ 0.01, equivalent to a fossil fuel cost of 1.6 \$/MMBtu (assuming that natural gas to produce steam would only have 80% HHV efficiency). Multi-stage evaporators with 1 lb of steam produce 10 lb of desalinated water. Therefore, 1 kWh produces 50 lb of desalinated water, while 1 m³ of water requires the steam by-product from producing 44 kWh electricity (21). At present, the cost of the energy for 1 m³ of desalinated water would be \$0.44, but this could be reduced to about \$0.25, the cheapest method for desalinating water. We also have to add the investment cost for the plant, which presently is 1200-1500 \$/daily m³. For a 1 GW plant this cost should be reduced to 600 \$/daily m³. Thus, we have to add 0.30 \$/daily m³ for present plants, and 0.15 \$/daily m³ for

larger plants. A 1 GW solar-based power plant (6500 hours/year) would produce about 150 million m³ water/year, or 45000 acre-feet of water. The potential for cogeneration of desalinated water on large scale is a major added advantage of solar thermal power.

6. Discussion and Conclusions

Our main objective is to show that solar thermal energy is ready for large-scale implementation, which should be included in our Government's long-range planning; it is renewable, affordable and less polluting. The US is one of the few developed countries that has sunny and warm desert areas sufficiently large for supplying all of its energy needs (see Table 9, and Figure 3).

A technology must be economically viable for large-scale implementation to occur. A most important result of our study is the realization that, for intermediate loads (50% of the US electricity requirement), solar thermal energy is already competitive with any new power plant, including old-fashioned coal power plants equipped with scrubbers. Although solar thermal energy is not yet competitive with other available technologies for base loads, it is a proven technology that can be modified for building more advanced plants that are cheaper and superior than any other energy source for producing the most urgent need of our national grid – variable, instantaneously dispatchable loads. Especially important is that, even for base loads, solar thermal energy is cheaper than sequestering CO₂ from coal power plants and it has the further advantage that we do not have to worry about the long-term effects of the sequestered CO₂. Our conclusion about the advantages of solar thermal electricity for intermediate and variable loads are so robust that even if we have underestimated the cost by 25%, the advantages would still remain. Therefore, solar thermal energy should become an important part of any plans to decarbonize our energy economy and reduce energy imports.

The authors are not suggesting a specific timetable, but only that the US should start planning for the reduction of our dependence on fossil fuels by switching slowly to an electric economy based

both on solar, wind and nuclear energy. If we start soon and advance at a much faster pace than we envision presently, our oil reserves will last for much longer and the dark future predicted by Goodstein (6) can be avoided.

We present an approximate estimate of the total cost based on the amount of electricity that would be needed to replace all of our energy needs. A mistake often made (22) is to equate kWh with BTU of fossil fuel on a strictly caloric basis. But, electricity can replace many of our present uses for fossil fuels with about double to triple the present thermal efficiency. To be conservative we will apply a factor of two.

Our total fossil fuel consumption is 84 Quadrillion BTU/year (see Table 10). At 3,400 BTU/kWh this translates to 25.0 trillion kWh. Dividing by two for the increased efficiency of electricity, this becomes 12.5 trillion kWh. At 6,500 operating hours/year this becomes about 2,000 GW installed capacity. To compensate for variations between summer and winter we would probably need 3,000 GW of installed capacity, which requires an area of approximately 60,000 square miles. Figure 3 and Table 9 show that this area is easily available in warm desert areas.

A fraction of the fossil energy use is not easily replaced by electricity. This includes: airplane fuels (3% of fossil fuels), and for chemicals (7% of fossil fuels). 40% of our oil is used for private cars and small trucks. 80% of the demand for gasoline can be replaced by hybrid cars equipped with plug-in batteries big enough for driving 40-50 miles, the remaining 20% (4% of fossil fuels) cannot be replaced. Railroads can replace large trucks for at least 60% of our shipping (the remaining 40%, equivalent to 2% of fossil fuels, cannot be replaced); while a fraction of our buses can be replaced by electric trams, they only consume 0.2% of fossil fuels. Therefore, the fraction of fossil fuels that cannot be replaced by electricity is 16 to 20%. Biofuels, while capable of providing only a small fraction of our total energy needs, could

provide all transportation fuels that cannot be replaced by electricity, and biomass should be reserved for this purpose.

We can estimate the cost of reducing the use of fossil fuels by 55%. This can be achieved by lowering our use of coal by 80%, oil by 50% and natural gas by 40%, and it would reduce CO₂ emissions by 60% (data for CO₂ emissions from Ref. 18) and eliminate all oil imports from outside the Western hemisphere. We would need about 1650 GW installed capacity, which would cost 5.6 trillion dollars or about 190 billion dollars a year over 30 years, which is definitely doable and affordable. This is a conservative upper limit. Proper mass production should cut this cost in half. To do this we must add the cost of expanding the grid, a much smaller amount. Furthermore, eliminating coal power plants and switching from oil to electricity involves political and market constraints outside the scope of this paper.

Solar thermal energy in the form presented here does not have to be the only source. It opens a seemingly superior way to address our need to replace fossil fuels. Large-scale use of wind and solar cells would, at equal cost, have significant advantage over sole reliance on solar thermal energy were it not for their lack of energy storage. At least half of the total electricity generation could be distributed over a much larger area of the US, thus reducing the load on the transmission system. There has been considerable discussion about advanced grids to average out the fluctuations of wind and solar cells. Solar insolation, however, is correlated by time of day across our whole continent. Furthermore, a grid cannot operate if all its inputs are variable and uncontrollable without access to a significant controllable, instantaneously-dispatchable electricity source. Our concept of solar thermal energy is uniquely qualified to play this role and provide not only instantaneously controllable energy, but also the equivalent of storage. This requires a more detailed and extensive investigation. But the concept is clearly feasible.

Experience with large-scale solar energy in the US could also be applied to the rest of the world. It would reduce the pressure on dwindling oil supplies and also, reduce the risk of nuclear proliferation, by providing developing countries with an alternative energy source. Furthermore, it could co-produce desalinated water on a large scale cheaper than any other technology. This is important in California and even more in the developing countries and southern Europe. Thus solar thermal energy merits much more serious attention than it has received until now. It is essential for the US Government to support its introduction now as the timescale for replacing fossil fuels is long. To wait is to risk global warming, dwindling oil supplies and economic catastrophe.

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Fossil Fuels	2728.7
Coal	1970.3
Petroleum	118.3
Natural Gas	629.2
Other Gases	10.9
Nuclear Electric Power	763.7
Renewable Energy	359.2
Conventional Hydroelectric Power	275.0
Wood	37.0
Waste	22.8
Geothermal	13.1
Solar	0.5
Wind	10.7
Other	5.1
Total Electricity Generation	3856.7

Table 1. Electricity Net Generation by Sources, year 2003.

Billion Kilowatthours.

(data from: <http://www.eia.doe.gov>)

Retail Sales	3500.0
Residential	1280.0
Commercial	1119.0
Industrial	991.0
Other	109.0
Direct Use	175.0
Total Electricity Consumed	3675.0

Table 2. Electricity Net Consumption by End Use, year 2003.

Billion Kilowatthours.

(data from: <http://www.eia.doe.gov>)

Loading	Capacity Factor	Percentage of Total Electricity Requirements
Base	CF > 57%	40.0
Intermediate	23% < CF < 57%	50.0
Peak	CF < 23%	10.0

Table 3. Capacity Factor for Various Load Demands.

(<http://www.eas.asu.edu/~holbert/eee463/ECONOMICS.HTML>)

Capacity Factor (CF): is the energy produced during some time interval ratioed to the energy that could have been produced at net rated power during the same time interval.

Case	Sargent & Lundy		
	Near Term	Mid Term	Long Term
Project	Trough 50	Trough 150	Trough 400
In Service	2004	2010	2020
Net Power (MWe)	50	150	400
Capacity Factor (%)	54	56	57
Solar Field (km ²)	0.569	1.632	4.349
Heat Transfer Fluid	VP-1 Oil	Hitec XL Nitrate Salt	Hitec XL
Solar Field Operating Temperature (°C)	391	500	500
Thermal Storage (hrs)	12	12	12
Thermal Energy Storage	Indirect 2-Tank	Thermocline Direct	Thermocline Direct
Thermal Storage Fluid	Solar Salt	Hitec XL	Advanced
Land Area (km ²) ^a	1.890	4.980	13.189
Total Plant Cost (\$/kWe)	4,816	3,562	3,220

Table 4. Trough Technology Summary for Sargent & Lundy Technology Cases (4).

a: estimates made by SunLab (4)

	Investment (\$/kW installed)	Hours per Year	Cost per kWh (cents/kWh)
Solar Thermal – Near Term (ref. 4)^a	4000*	4900	8.0
Solar Thermal – Future (ref. 4)^a	3220	4900	6.2
Conventional Coal Power Plant (with Scrubbers) (refs. 15, 17)^b	1200	6500	4.5
Clean Coal (ref. 15)^b	1550	6500	5.6
Clean Coal (ref. 15)^b (with CO₂ sequestration in the plant –no provisions for the cost of ultimate sequestration)	2000	6500	7.0**
Nuclear (ref. 17)^b	2200	6500	6.0
Solar Cells – Present (ref. 18)^{***} (Installed)	> 6000	2500	> 22.5
Solar Cells – Future (ref. 1)^{***} (Installed – DOE Projections)	2000	2500	7.5

Table 5. Electricity Costs for Solar Thermal Plants Compared to Coal, Nuclear and Solar Cells.

(a: 400 MW plant; b: 1 GW plant)

*: the estimate was obtained as follows:

near term estimate in ref. 4: 4,816 \$/kW installed

20% scalable with exponential scale-up factor of 0.6 saves 540 \$/kW installed

8 parallel trains built simultaneously should save 10-20% of the non-scalable part of the plant, for a saving of 380-760 \$/kW installed.

** : The cost of ultimate sequestration in either a geological formation or in the deep ocean, including pipelining the CO₂ to the point of sequestration, strongly depends on the location of the plant, and can vary significantly. But, it is substantial increasing the total cost of electricity well over the cost of solar thermal energy.

***: For solar cells we give reported average kWh per year per peak watt capacity.

	Intermediate (cents/kWh)
Solar Thermal – Near Term**^a	8.0
Solar Thermal – Future**^a	6.2
Conventional Coal**	8.0
Clean Coal***^b	10-11
Clean Coal***^b (with CO₂ sequestration in the plant –no provisions for the cost of ultimate sequestration)	12-13
Nuclear**^b	10.0-11.0
Solar Cells – Present	Cannot supply it

Table 6. Cost per kWh for Intermediate Power.
(a: 400 MW plants; b: 1 GW plants)

*: The solar thermal plant estimated by S&L (4) is an intermediate plant. For a base load solar thermal plant the total investment cost would increase with the time that is operated, but the cost per kWh would only increase slightly.

** : Intermediate load is a fixed load for 13 hours a day (8 a.m. to 9 p.m.), whereas base load is for 24 hours a day. As the plant is only operating 13/24, or 54%, of the time, the capital related charges are 85% larger, while the cost of coal per kWh, which is 1.2 cents, remains constant.

We do not have a breakdown of the cost of nuclear energy, so we give an approximate estimate.

***: the clean coal power plants, which are based on a gasifier coupled with gas turbines, are really base load. In fact, a gas turbine is fast to start-up (about 1 hour), but it is very inefficient when it operates below 80% capacity. On the other hand, a gasifier can operate well at low load, but it requires at least half a day for start-up.

No information has been published on how clean coal power plants would operate on intermediate load. One way is to operate the gasifier at low load for part of the time, and shut down some of the turbines. The estimate is therefore only approximate.

	Trough
Year	2020
Capacity (MWe)	400
Capacity Factor (%)	56.2
Capital Cost (\$/kW)	3,220
Annual O&M Cost (\$)	14,129,000
Levelized Energy Cost (\$/kWh)	0.0621
Economic Life (Years)	30
General Inflation (%)	2.5
Equity Rate of Return (%)	14.0
Cost of Construction (%)	7.0
Construction Duration (Year)	1
Investment Tax Credit (%)	10.0
Taxes (%)	40.2
Depreciable Life (Years)	5
Internal Rate of Return (%)	14.0
Debt Service Coverage Ratio	1.35
Ownership	IPP

Table 7. Economic Assumptions Listed by Sargent and Lundy (4) to Compute Cost per kWh in Table 5.

	Incremental Investment	Load Following (cents/kWh)
Solar Thermal – Near Term^a	1800	10.4
Solar Thermal – Future^a	1380	8.0
Conventional Coal	1200	15.0
Clean Coal^b	Not Suited	Cannot supply it
Clean Coal^b (with CO₂ sequestration in the plant –no provisions for the cost of ultimate sequestration)	Not Suited	Cannot supply it
Nuclear^{*b}	2500	20.0
Solar Cells – Present	Not Suited	Cannot supply it

Table 8. Incremental Investment for Load Following Capability. Ability to Provide 1 kW incremental load following Capacity for 5 Hours a Day.**

(a: 400 MW plants; b: 1GW)

*: we do not have a breakdown for nuclear energy giving separate capital related cost, fuel, and other costs. Our estimate is based on assuming capital related cost is 80% of total costs.

**: For coal and nuclear energy the investment is the same as in Table 5. For solar thermal energy the amount for the steam plant, 14% or \$600, stays constant, but the investment for collectors with storage is reduced proportionally to time of operation required (here a factor of three).

Desert	Location	Size (Square Miles)	Rainfall (inches/year)
Mojave (or Mohave)	Arizona, California, Nevada	25,000	< 5 (most areas get < 2 mostly in winter)
Sonoran	Arizona, California, Mexico	120,000	4-12 (most areas get < 6 year around)
Chihuahuan	Arizona, New Mexico, Texas, Mexico	175,000	6-8 (mostly in summer)
Great Basin[*] (Sagebrush Steppe not included)	Idaho, Nevada, Oregon, Utah	160,000	7-12 (mostly in winter also as snow)

Table 9. Total Area and Rainfall in the North American Deserts.

^{*}: not all the area of the Great Basin desert has a solar radiation suitable for efficient solar energy generation.

Petroleum	39.073
Residential	1.546
Commercial	0.753
Industrial	9.436
Transportation	26.131
Electric Power	1.207
Natural Gas	22.508
Residential	5.244
Commercial	3.217
Industrial	8.317
Transportation	0.668
Electric Power	5.062
Coal (Includes Coal Coke Net Imports)	22.757
Residential	0.010
Commercial	0.083
Industrial	1.776
Transportation	0
Electric Power	20.888
Renewable Energy	6.150
Residential	0.435
Commercial	0.106
Industrial	1.751
Transportation	0.239
Electric Power	3.619
Nuclear Electric Power	7.973
Total Energy Consumption	98.461

Table 10. Energy Consumption by Sources and by End Use, year 2003.

Quadrillion Btu.

(data from: <http://www.eia.doe.gov>)

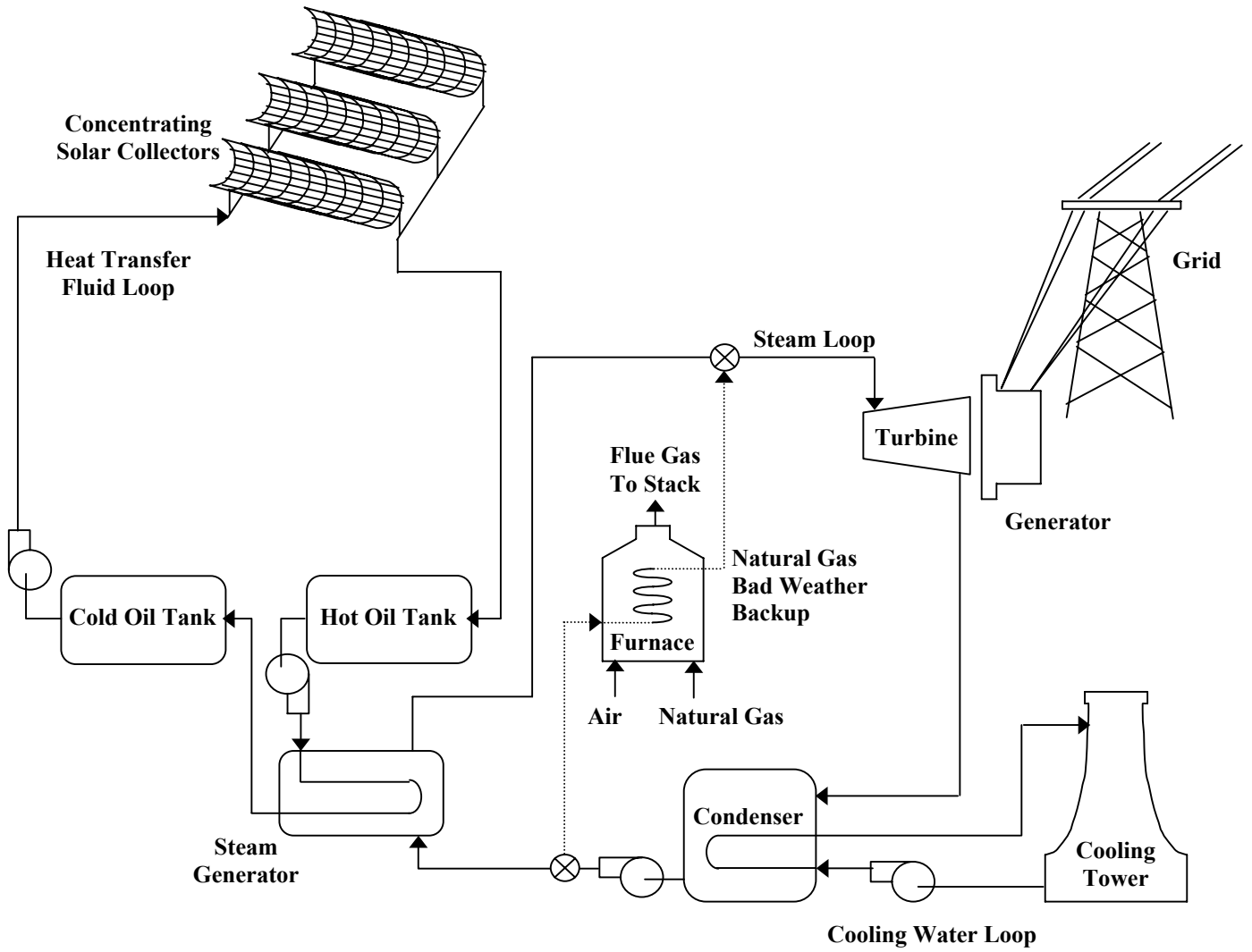


Figure 1. Schematic Diagram of a Solar Thermal Power Plant with Storage.

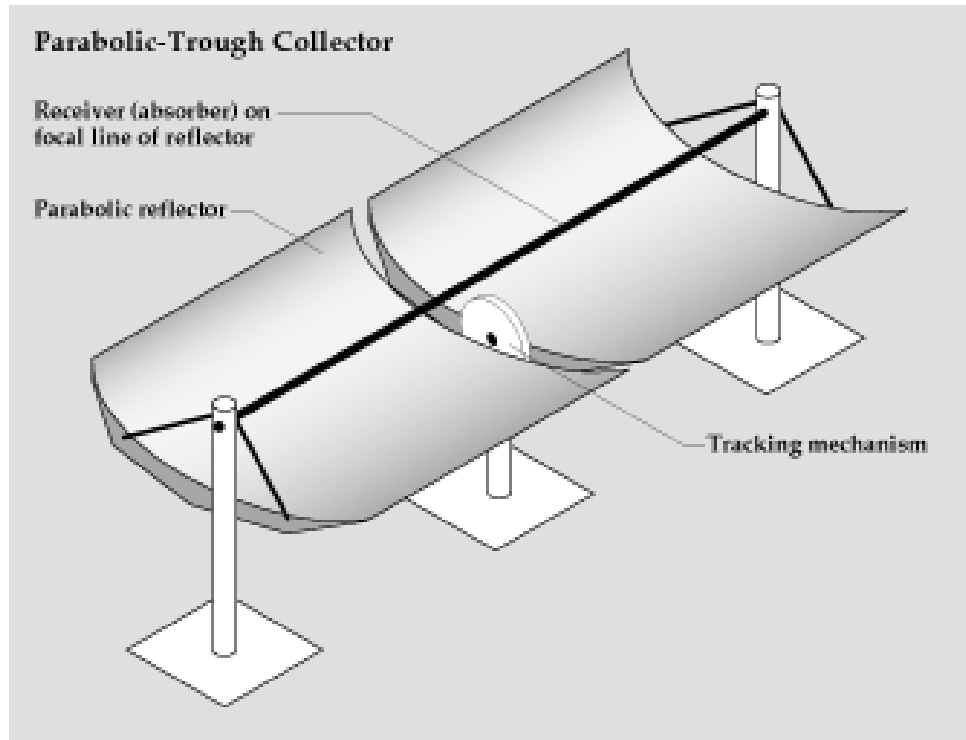


Figure 2. Schematic of Parabolic Trough Collectors.

(schematic from: www.eere.energy.gov/solar/sh_basics.html)



Figure 3. North American Deserts.

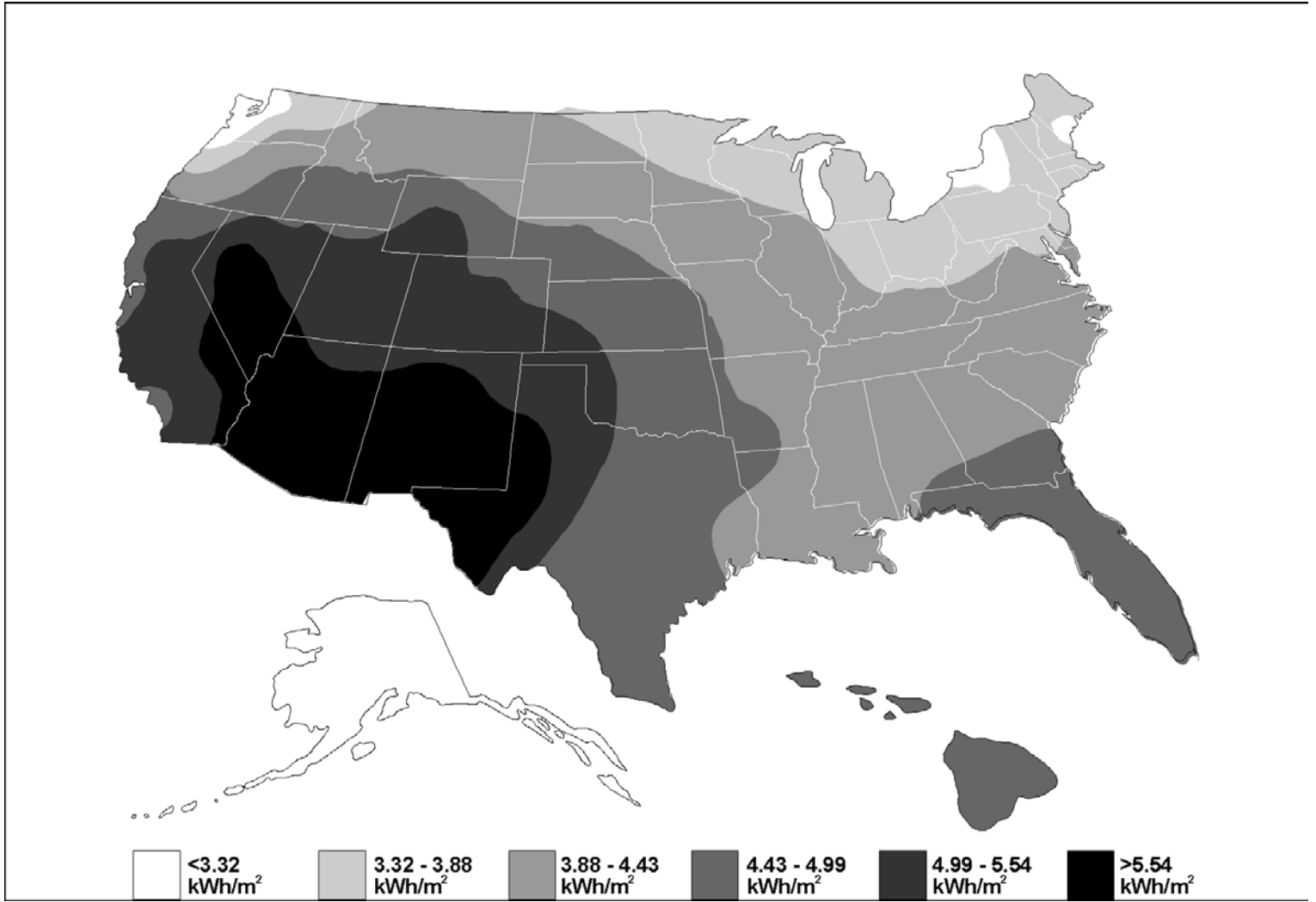


Figure 4. Average US Daily Global Solar Radiation.

(map from: <http://www.eia.doe.gov>)