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Solar thermal energy: The forgotten energy source

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Abstract

Solar thermal (ST) energy, using trough solar collectors, can be an environmentally friendly and economically competitive electric source for any part of the world (such as the USA) that includes large desert areas. Competitive ST involves trough solar collectors, which concentrate solar rays onto a flowing liquid able to sustain very high temperatures ($\geqslant$800°F) without exerting significant vapor pressure or decomposing. This allows the solar energy to be used to raise steam and drive turbines of electricity-generating plants directly, or to be harvested and stored as sensible heat in large underground ponds. The stored portion of the energy can be used instantaneously to meet variable power needs. This technology has been amply demonstrated by a 354 MWe modular plant (consisting of 9 ST units) that has been running in the Mojave Desert for the past 20 years. For intermediate loads (50% of the US electricity requirement) ST energy is already competitive with any new power plant, including old-fashioned coal power plants equipped with scrubbers. ST energy, using trough solar collectors, can become a major technical, financial, and political development.

Keywords: Solar Thermal energy; Solar collectors; Electricity-generating plants; Environmentally friendly power source; Renewable energy; CO_2 emissions

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1. Introduction

The purpose of this paper is to demonstrate that, contrary to common belief, solar thermal (ST) energy can meet all criteria for a major, environmentally friendly, and economically competitive electric power source for any part of the world, such as the USA, that includes large desert areas. We would hope to generate support and momentum for what we believe would be a major development on technical, financial, and even political grounds, with major national and international benefits.

The concept involves trough solar collectors, which concentrate solar rays onto a flowing liquid able to sustain very high temperatures ($\geqslant$800 °F) without exerting significant vapor pressure or decomposing, thus allowing the solar energy to be used to raise steam and drive turbines of electricity-generating plants directly, or to be harvested and stored as sensible heat in large underground ponds. The stored portion of the energy can be used instantaneously to meet variable power needs. This technology has been amply demonstrated by a

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354 MWe modular plant (consisting of 9 ST units) that has been running in the Mojave Desert for the past 20 years (Appendix A).

Our argument in favor of ST rests on the fact that this type of energy: (a) can be uniquely and efficiently stored for use at will, and (b) its use is not encumbered by cleanup requirements as is the case for fossil fuels (scrubbing of polluting gases, sequestration of greenhouse gases), or for nuclear power plants (radioactive mining tails, radioactive waste treatment and disposal). The implication of (a) is that the energy-generating (actually harvesting) portion of the plant can be decoupled from the electricity generating portion to great economic advantage since 60% of our electricity needs are for variable power, from 8:00 am to 9:00 pm; that is, a power requirement greater by a factor of 1.5 than base load which covers an entire 24 h period (40% of the total demand). Eighty percent of the variable load falls within reasonable narrow bounds and is called intermediate load, while 20% has large fluctuations over short periods. The economic impact of ST is even larger when item (b) is also taken into account.

Our assertions are based on straightforward scaling from recently available and widely scrutinized economic estimates for ST [1], which missed the main point (the advantages noted above), as did many extensive reviews including one by the National Research Council [2]. The results of our analysis lead to the conclusion that ST energy can supply ~60% of our electricity needs at competitive rates by means of a technology that is already at hand. The potential of ST to supply so large a share of our energy needs was not recognized because all others based their estimates on base load alone. Moreover, the very significant advantages to be derived from economies of scale, which may be attained through a large-scale deployment of the technology, were not considered. Furthermore, we show that the needed US desert area is readily and cheaply available.

As ST technology has an instantaneous load-following capability not matched by any other clean technology, aside from hydroelectric, it can be used to compensate for large fluctuations in the grid caused by the use of wind and solar cells. ST can also be coupled with water desalination, subject of great importance in California and in many areas of the world.

2. The issue of variable electricity loads

Consider a coal or a nuclear power plant that provides base load (24 h/day). The cost of 1 kWh is the sum of the fuel price plus a fee related to the capital investment. This fee includes capital recovery, taxes, maintenance and operating costs. A typical breakdown is given in Table 1.

Such costs are normally based on the total annual capital expenditure divided by the total number of kWh the plant generates per year (8760 h multiplied by the total capacity of the plant and by the capacity factor).

Table 1
Economic assumptions listed by Sargent and Lundy [1]

	Trough
Year	2020
Capacity (MWe)	400
Capacity factor (%)	56.2
Capital cost ($/kWe)	3220
Annual O&M cost ($)	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

The capacity and the total capital charges per year are function of rated capacity only and are fixed whether the plant operates at full or reduced capacity. Therefore, if the plant produces only 20% of its maximum capacity, the capital related charges per kWh will be 5 times that of a base power plant. For a ST power plant this factor is much smaller as the hot heat transfer fluid (HTF) can be stored for a whole day and the collectors and the storage facilities can be designed to handle the exact amount of HTF required for the total daily output, regardless of its distribution over time. Only the steam power plant has to be designed for maximum capacity. Since the cost of the steam power plant for a large ST base plant is only 10% of the total investment, the increase in capital expense per kWh for a plant operating below maximum capacity and producing Z kWh per kWe installed capacity is only $[0.9+0.1\times 24/Z]$ (0.9: fraction of the total investment — collectors, HTF and storage facilities — that depends on actual daily kWh output, and not on total kWe installed capacity; 0.1: fraction of the total investment—steam power plant — that depends on total kWe installed capacity, and not on actual daily kWh output). For ST power plants, if the total output is only 20% of the maximum capacity the capital charges per kWh increase by a factor of 1.4 (a factor 3.6 times less than for coal or a nuclear power plants).

The ability of ST plants to deliver the intermediate and load-following power required for specific applications is a unique capability that makes ST power competitive today. This ability, rather than the cost of base power for coal and nuclear power plants (as used in [2]), should serve as the basis upon which to judge the economic feasibility of ST technology. In the next section we provide evidence that our basic premises for rescaling costs are sound and robust. We have relied only on current technologies and data, and not on speculative advantages due to the economies of scale. Experience has shown that, in reality, such cost savings are to be expected.

Prior to 1992, the cost of idling capital investment was masked by government guarantees, which allowed public utilities to levy fees based on a return on investment; so, it became economically attractive to build plants with a large excess capacity. This was feasible because coal power plants can be run at a very small fraction (~12%) of their design capacity. After the guarantees disappeared this method of operation could no longer be sustained. Instead, peak demand periods were served by special on–off switches, such as gas turbines fueled by natural gas. This option is not included in our comparison as costs have increased by a factor of 5 over the last 10 years and it is hard to make predictions for the future. For such plants, however, efficiency deteriorates when they operate at lower than 80% of design capacity. As coal and nuclear plants are not fast-followers, they have to be put on line, each day, 1–2 h before needed. The new clean coal power plants are based on gasifiers, but they too use gas turbines and have similar problems that require specifically design with on–off control. The cost of constructing nuclear plants for load following is very high and the possibility of identifying possible coolants for nuclear plants that could allow for an increase in storage capacity is speculative. No such design is currently available or in development.

3. Estimated costs for ST energy

Our cost estimates are based on the recent Sargent and Lundy report on ST energy [1] commissioned by the US DOE and reviewed by the National Research Council. It presents an evaluation of the Luz technology and its performance based on the plants built in the USA, developments at DOE, and other related technology. These authors present cost estimates for the trough-collector technology, which are summarized in Table 2. A detailed breakdown of costs based on current prices for proven technology is given in Table 1.

We have scaled our estimates from 50 to 400 MWe capacity, a more reasonable size for large-scale energy use, which should lead to significant costs reduction. The near term estimate for ST is for 4900 h a year (Table 2), assuming a 100% capacity factor. This averages out to 13.5 h per day at intermediate load, a preferred design for the initial plants. The cost per kWh for base power would be very similar. Our estimate of 4,000 $/kWe installed (Table 3) was obtained as follows: the near term estimates in Ref. [1] is: 4816 $/kWe installed. Twenty percent scalable with an exponential scale-up factor of 0.6 saves 540 $/kWe installed. If 8 parallel trains are built simultaneously, 10–20% of the cost of the non-scalable part of the plant (an additional 380–760 $/kWe installed) could be saved. The total potential saving would be 920–1300 $/kWe installed.

Table 2
Cost estimates for the trough technology

Project	Sargent & Lundy		
	Near term Trough 50	Mid term Trough 150	Long term 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 (h)	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)	1.890	4.980	13.189
Total plant cost ($/kWe)	4816	3562	3220

Source: Sargent & Lundy Study [1].

Table 3
Electricity costs for solar thermal compared to coal and nuclear

	Investment ($/kWe installed)	Base (cents/kWh)	Intermediate (cents/kWh)	Load Following (cents/kWh)
Solar thermal—near term [1]	4000[a]	8.0[b]	8.0	10.4[d]
Solar thermal—future [1]	3220	6.2[b]	6.2	8.6[d]
Conventional coal power plant (with scrubbers) [3]	1200	4.5[c]	8.0	13.5[e]
Clean coal [3]	1550	5.6[c]	10	Cannot supply it
Clean coal [3] (with CO_2 sequestration in the plant)	2000	7.1	11.5	Cannot supply it
Including ultimate disposal		11.0	15.5	
Nuclear [4]	2200	6.0[c]	10–11	Cannot supply it

Base, intermediate and load following.

[a] Explanation of estimate in Section 3.

[b] Operated 4900 h/year.

[c] Operated 6500 h/year.

[d] A power plant designed to supply, for each kWe installed, 12 kWh a day of variable electricity at instantaneous maximum rate of 4 kWh.

[e] Designed for the same load following capability as in *d*.

Ours are very conservative estimates as the cost reduction realized by building a large plant would be significantly larger. When the ST technology is widely applied, the cost should be reduced by a much larger factor. Seventy percent of the total investment is in the collectors, which could be mass-produced. Our experience with mass production indicates that the cost of the collectors could be lowered by a factor of 3, leading to an overall reduction by a factor of 2. This would make ST competitive with any other source for base power.

Mass production provides another big advantage. In developing countries, the need is for small plants, 2–50 MWe capacity. Mass produced collectors would make small power plants feasible because each collector is limited in capacity (4–5 kWe) to ensure transportability. Mass production also provides a significant advantage for the future. The labor force needed for constructing nuclear and clean coal power plants must be highly skilled. Mass-produced ST plants could be designed so that the need for assembly by skilled labor would be minimal.

4. Comparison of costs

In Table 3 the costs projected above, for ST technology operating intermediate load, are compared—per kWh—with published data for coal power plants at base load. The approximate cost of nuclear is also shown, although few, if any, such plants have been built for nearly 20 years; this makes cost projections very difficult to estimate. Other potential sources of power such as gas turbines and solar cells are not included. With gas prices increasing by a factor of 5, over the last 10 years gas turbines have fallen out of favor, while solar cells are still too expensive to be used for feeding the grid. Coal offers several options including "clean coal", and "clean coal with shift and CO_2 removal, including ultimate sequestration". While the cost estimates for clean coal with or without CO_2 removal are based on demonstration plants, the cost of ultimate sequestration is only an estimate. Costs estimates for the ultimate disposal of CO_2 are not available, but they can add significantly to the financial burden. A similar case can be made for the cost of handling nuclear waste disposal, which is yet to be addressed.

The cost estimates for clean coal, with and without CO_2 sequestration, come from an EPRI report [3]. Proposals for the new safer nuclear power plants that have been bid, but not built, range from \$1500 to \$2500 per kWe installed. At this time the first steps are being taken with the US Government sharing 50% of the cost with a number of utilities. In our estimates the costs we use is \$2200/kWe [4], although an exact figure is not critical to our analysis. Even now, however, ST has become competitive for base load with clean coal with CO_2 sequestration when the ultimate cost of CO_2 sequestration and pipelining are included (Table 3). This very important cost must be taken into account in any plan for reducing greenhouse emissions.

In Table 3 we also give estimates for intermediate load applying the method presented in Section 2 to a rescaling for intermediate loads. ST is competitive even with conventional coal, and it provides a significant cost advantage over clean coal, and nuclear. Finally, Table 3 gives the same estimates for plants designed to rapidly load follow over a large range of power output. The only technology presently available for doing so is conventional coal power plants, which are the main tool for dispatchers to control the grid. ST has here a potential edge, and such plants are the most attractive application of ST today, as they are already cost competitive.

5. Combined production of electricity and desalinated water

A detailed discussion of electricity and desalinated water cogeneration in a steam power plant is beyond the scope of this paper, but it is an available technology [5,6]. Cogenerating steam power plants could fill the great need for water not only in the USA, but also throughout the world, especially in developing countries. The main interest in ST power in the Mediterranean area, where large desert areas are located close to the sea, 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 backpressure turbine, that condenses steam at 240 °F, can reduce the output of power by ~12% and produce 5 lb of steam per kWh at a cost of \$0.01—equivalent to a fossil fuel cost of 1.6 \$/MMBtu, assuming that the natural gas needed to produce steam would have 80% High Heat Value (HHV, which accounts also for the heat coming from condensing the steam) efficiency. Multi-stage evaporators produce 10 lb of desalinated water per lb steam fed. Therefore, 1 kWh produces 50 lb of desalinated water, while 1 m^3 of water requires 44 kWh electricity [6]. At present, the cost of the energy for 1 m^3 of desalinated water is \$0.44, but using ST this could be reduced to about \$0.25. No method for desalinating water is cheaper than co-production with ST. However, we should add the investment cost for a desalination plant, which presently is 1200–1500 \$/daily m^3. For a 1 GWe plant, this cost could be reduced to 600 \$/daily m^3. Thus, we must add 0.30 \$/daily m^3 for existing plants, and 0.15 \$/daily m^3 for larger plants. A 1 GWe solar base power plant (6500 h/year) would produce about 150 million m^3 water/year, or 45,000 acre-feet. The potential for cogeneration of desalinated water on a large scale is a major added advantage of ST power.

6. Compensation for variable power plants and load in the grid

Variable power requirements are a problem for the grid because of variations on the consumer end. In the future, wind and solar cells have the potential to become important electricity sources, but their use is strongly limited by their lack of storage capacity and their strong variability. ST plants, however, are uniquely suited for large-scale load following. With such plants, it would become possible to design an advanced grid based on ST, nuclear, wind and solar cells because ST has the ability to compensate for variations both in demand and power inputs into the grid. This concept is clearly feasible, but further study would be required to evaluate its potential quantitatively.

7. Concluding remarks

A technology must be economically feasible before large-scale implementation can occur. The most important result of our study is the realization that for intermediate loads (50% of the US electricity requirement) ST energy is already competitive with any new power plant, including old-fashioned coal power plants equipped with scrubbers. Although ST 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 to other energy sources for producing the most urgent need of our national grid: variable, instantaneously dispatchable loads. Especially important is that, even for base loads, present ST energy is competitive with coal power plants equipped for sequestering CO_2 (the cost of which depends on location, and is at least 0.01 \$/kWh). Furthermore, with ST any adverse effects of sequestered CO_2 can be avoided. The advantages of ST electricity for intermediate and variable loads are so robust that they would remain attractive even if our estimates were 25% below the actual cost. ST energy should become an important part of any plan to de-carbonize our energy economy and reduce energy imports. Through large-scale construction we can mass-produce the collectors and reduce costs by a factor of 2.

The cost estimates given here are for ST power plants with water-cooling. Many deserts are located near a water source sufficient for producing the first 50–100 GWe. However, it is unlikely that a desert water source could produce an output of 1000–2000 GWe total electricity; furthermore, the use of that much water could impact on the local climate. This problem could be circumvented by air-cooling, an available technology. Since desert temperatures can reach 120 °F, steam power plants would have to be modified with backpressure 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. However, once the first 50–100 GWe ST power plants have been built, the electricity price would be less than 0.06 \$/kWh, probably less than 0.05 \$/kWh.

We present an approximate estimate of the total costs based on the amount of electricity that would be required to replace all of our energy needs. We use this approach to illustrate the potential of ST to meet this goal. Preferably, our future energy needs should be supplied from a variety of different sources. A mistake often made 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 2.

The US total fossil fuel consumption is 84 quadrillion Btu/year [7]. At 3,400 Btu/kWh this translates to 25.0 trillion kWh. Dividing by 2 for the increased efficiency of electricity, this becomes 12.5 trillion kWh. At 6500 operating hours/year this becomes about 2000 GWe installed capacity, which requires an area of approximately 30,000 square miles (see Appendix B). Fig. B.1 and Table B.1 show that this area is easily available in warm North American deserts, where the average daily solar radiation is high (Fig. B.2).

A fraction of the fossil energy use is not easily replaced by electricity. This includes: airplane fuels (3% of fossil fuels) and chemicals (7% of fossil fuels). 40% of our oil is used for private cars and small trucks. Eighty percent 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 16–20%.

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%; this would reduce CO_2 emissions by 60% (data for CO_2 emissions from Ref. [7]) and eliminate all oil imports from outside the Western hemisphere. We would need about 1100 GWe installed capacity, which would cost 4–4.5 trillion dollars or 130–150 billion dollars a year over 30 years, which is definitely doable and affordable. To this we must add the cost of expanding the grid, a much smaller amount.

Eliminating coal power plants and switching from oil to electricity involves political and market constraints outside the scope of this paper. By demonstrating the feasibility of ST power plants, and through their mass production, the USA can make a large impact on the rest of the world. Coupling ST power with water desalination in developing countries will help establish a de-carbonized economy worldwide.

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Appendix A

Arnold Goldman [8] developed parabolic solar collectors that store heat in a HTF at high temperatures. Godfrey [9] gives a simplified overview of this innovative technology.

Fig. A.1 presents a schematic diagram, and more detailed descriptions of existing plants are given in [10–13]. 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 Fig. A.2); other concentrating collectors could be substituted.

The collectors heat a HTF that is stable between 750 and 800 °F (poly-aromatic Dowtherm A, silicon-based fluids, or molten salts at temperature higher than 800 °F) as it flows through a set of pipes. The hot HTF is

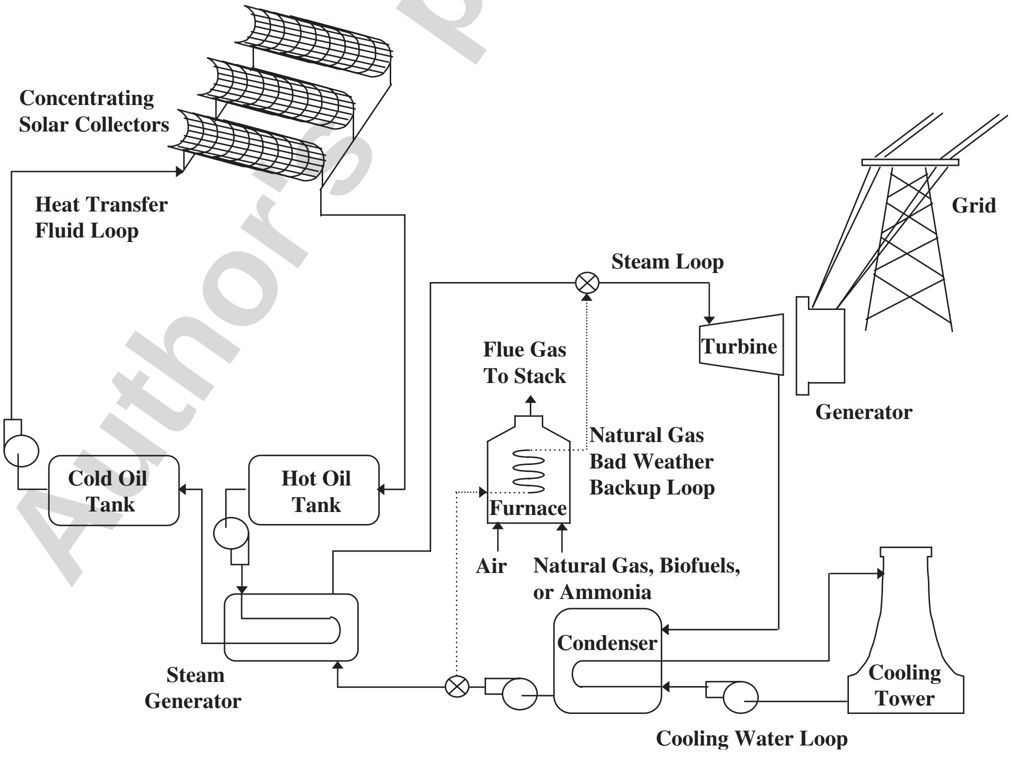

Fig. A.1. Schematic diagram of a solar thermal power plant with storage.

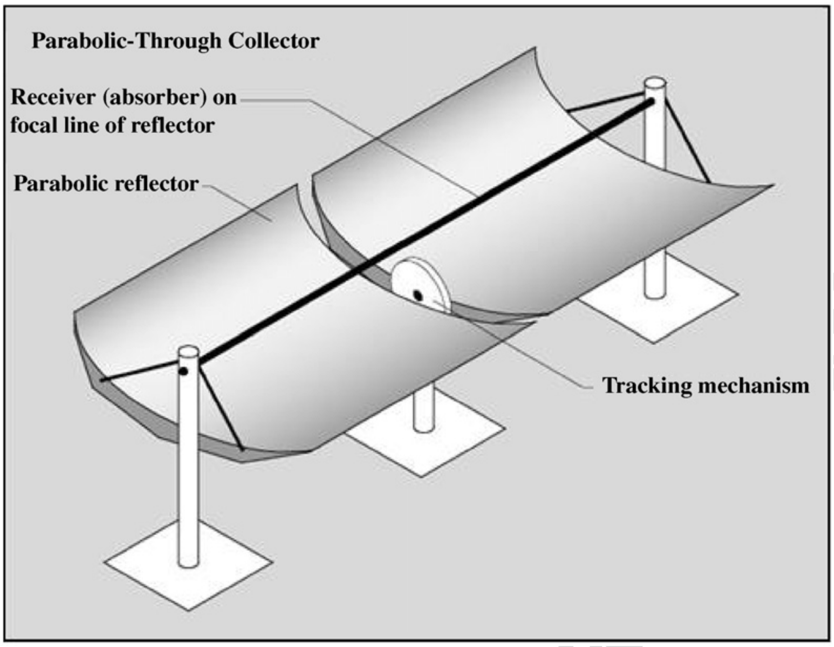

Fig. A.2. Schematic of parabolic trough collectors. *Source*: http://www.nemmar.com/asp-rel-articles/images/asp-i01/home-i166.jpg.

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, and in the future with biofuels or ammonia made from H_2 produced from solar energy. 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 (about 30% for a plant over-sized by a factor of 3) and has a small impact on thermal efficiency.

In the 1980s, Goldman founded Luz, a company that built 9 ST energy units in California, for a total of 354 MWe, that are still operating today [8]. 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 [8]. 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 ST plants have been built since Luz collapsed. Had the tax credits continued, the USA might 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 [1,12,13]. Ours is based on a comprehensive study by Sargent and Lundy for DOE [1] on the status of the technology and the cost of a large, updated Luz-type plant.

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.

Appendix B

Table B.1 and Fig. B.1 give data on the available desert areas in the USA, while Fig. B.2 shows the average daily solar radiation. Table 2 gives the near term land requirements for a 50 MWe plant as 1.9 km^2, or 0.74

Table B.1
Total area and rainfall in the North American Deserts

Desert	Location	Size (square miles)	Rainfall (in./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)

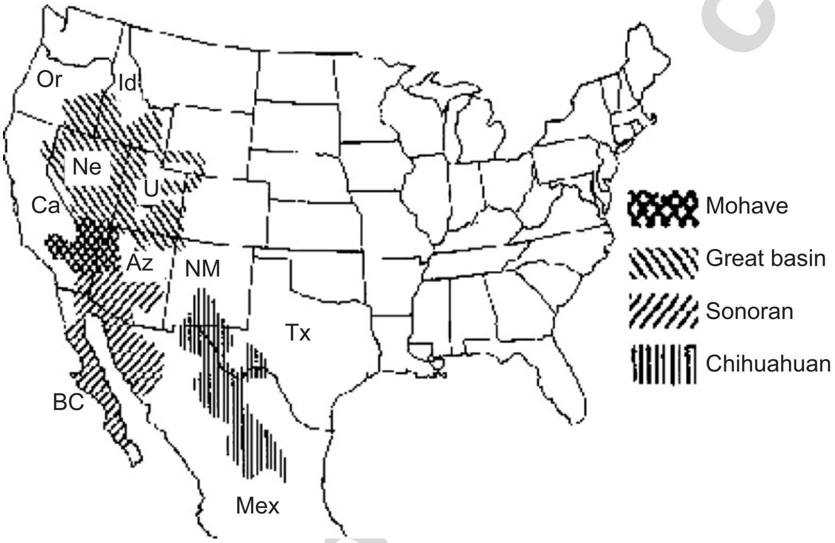

Fig. B.1. North American Deserts.

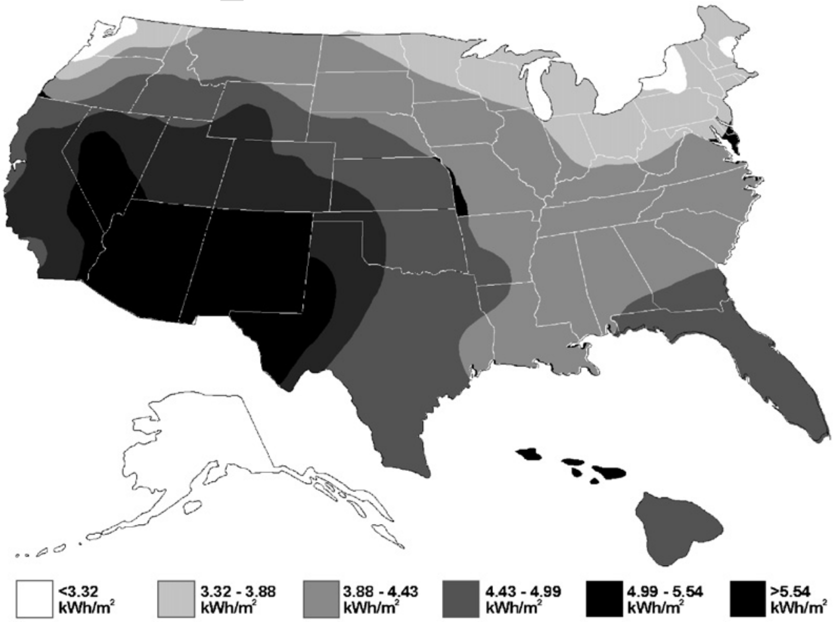

Fig. B.2. Average US daily global solar radiation. *Source*: http://www.eia.doe.gov.

square miles. Thus, 1 GWe requires 14.8 square miles, and 2000 GWe (sufficient to generate our total energy need) would require about 30,000 square miles. Therefore, there is no question that we will have enough desert area.

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