SOLAR THERMAL ELECTRICITY AS THE PRIMARY REPLACEMENT FOR COAL AND OIL IN U.S. GENERATION AND TRANSPORTATION

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Abstract

Advanced solar thermal electric options are dropping in price and some companies are beginning to introduce thermal storage. This paper suggests not only that Solar Thermal Electricity (STE) has sufficient diurnal and seasonal natural correlation with electricity load to supply the great majority of the US national grid (and by logical extension, those of China and India) on an annual basis with only 16 hours of storage. The correlation between the natural output and load exceeds 90% California and Texas, and also on the entire US grid. Furthermore, STE can supply much of the transportation market without destroying these natural correlations. The almost complete elimination of both fossil fueled generation and oil usage for transportation in the USA appears to be technically feasible.

Introduction

This paper is intended to stimulate thinking about an integrated renewable energy strategy to fully power the USA grid. The sun is a much larger practical energy resource than any non-direct solar resource. This paper presents solar electricity as the most likely means to nearly eliminate contributions to global warming from electricity generation by mid-century. Because thermal storage is much cheaper than electrical, mechanical or hydrogen storage, solar electricity will probably be predominantly in the form of solar thermal electricity (STE) with thermal storage rather than photovoltaic solar electricity with electrical or mechanical storage. In this paper we use the term STE rather than the less specific name Concentrating Solar Power (CSP) because CSP also includes PV concentrators (CPV), which do not have the crucial storage benefits of STE.

Figure 1. Visualization of the proposed 177 MW plant at the Carrizo Plain, California. Tracking linear reflectors focus solar energy on elevated boiler tubes to produce steam.

STE uses a field of solar reflectors to create a hot fluid to run a heat engine such as a Rankine or Brayton cycle. STE is a proven concept using Rankine cycle turbines. It has been successfully demonstrated in the Californian desert for two decades using commercial **parabolic trough technology**[1] and steam turbines, achieving an annual field availability of 99%. The US National Renewable Energy Lab uses a conservative future total plant availability of 94%[1], due primarily to O&M requirements of the conventional steam turbine used. **Central receiver (CR) technology**, in which a small receiver on a high tower is illuminated by a field of mirrors below, has also been developed using two-axis tracking heliostat reflectors and a commercial plant PS10 has begun operation in Spain. A third option recently developed is the **linear Fresnel reflector (LFR)** system in which long steam pipe receivers on towers are illuminated by long heliostats below[2,3]. Our CLFR (compact LFR) system (Fig. 1) is the basis of a recently announced 177 MW project with the PG&E utility in California[4]. Both CRs and LFRs currently generate steam directly with low parasitic pumping losses and could be used in GW-sized fields.

STE can use low cost energy storage in artificial thermal reservoirs. Oil storage was successfully demonstrated commercially in the mid 1980's[6] and molten salt is being commercialized in parabolic trough plants in Spain[7]. Very low cost water-based thermal storage is expected to be commercialized within two years using own technology under development. Thermal storage can actually lower kWh cost because it reduces turbine size required for a given thermal output. In STE designs using storage and no fuel, there is long term also immunity from fuel cost rises.

Currently, STE kWh cost is transitioning the cost of natural gas generation in California and is expected to be near US new plant coal generation cost when plants get to 500 MW - 1 GW scale in a few years. Any technology which can displace coal and gas generation could also potentially eliminate vehicle emissions using plug-in electric vehicles. Both markets are examined in this paper from a technical point of view, without detailed reference to economics. The correlations of solar output power with grid load requirements are examined with reference to 2006 load data.

Load Model

The data on the Californian grid usage is based upon hour by hour grid load data from California (CAISO)[8] and Texas (ERCOT)[9]. These loads are shown in Figures 2-5. A simple vehicle usage model was developed by the authors from energy use data from the sources provided for Fig. 5.

Collector Model

The collector model used in this paper is part of the project model developed commercially for the CLFR system (Fig. 1). However, any solar system with the same number of hours of storage will exhibit broadly similar correlations. The model uses ray trace results (two models have been used, an internally developed one and SolTrace from NREL for model checking) to form an sun angle map of optical performance vs sun position in the sky. The maps are incorporated into a TRNSYS model of the collector and power system, which can incorporate storage modules. A simpler project model with project financial modules also is provided with a collector and storage performance modules that are cross-correlated with the TRNSYS model to ensure accuracy. The project model is run for every hour of the year and, where possible, load data is entered also on an hourly time step. Both TRNSYS and the project model develop a value for collected solar radiation from archived solar radiation data, e.g. as available from the US National Renewable Energy Laboratory (NREL)[10].

The individual power block peak thermal efficiency was assumed to be 33%, but this assumption does not affect the basic conclusions of the paper, which could be for any turbine size and efficiency since we are not looking at detailed cost in this paper. The plant fleet size is arbitrarily made to equal the peak load requirement of the state or country being modeled. In this paper we use 50 GW for California, 63 GW for Texas, and 1067 GW installed and 789 GW non-coincident peak load for the USA (2006 data year).

The solar multiple is the ratio of actual solar array size to the minimum size required to run a turbine at full capacity at solar noon in mid-summer. Solar multiples greater than one are required when delivering power outside daylight hours using storage. We use the short form SMx to indicate a solar multiple of x. The storage used is only enough to carry load for 1- 2 days, and is used to match hourly output fluctuations in solar input with hourly load. These storage levels do not provide seasonal or even weekly storage, so are subject to local weather events, especially sustained cloudy periods.

However, with the CLFR, we also use solar multiples of up to 2 even when not using storage; this causes overproduction of thermal energy at peak solar periods in summer (discarded by turning some of the reflector field off-focus) but allows better utilization of the turbine at other times, increasing plant capacity factor. Because our models currently show improved economics using a solar multiple of 2 in fields without storage, we use SM2 as the non-storage configuration with the best correlation with grid load in this paper.

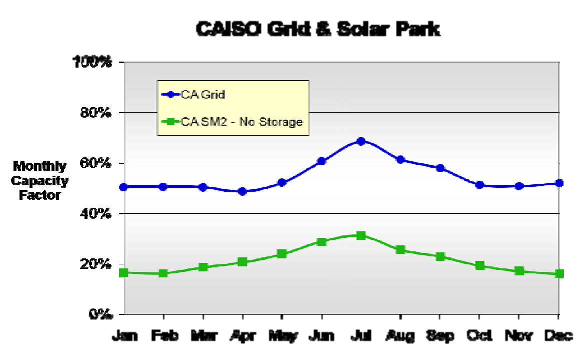

Figure 2. Solar contribution to grid load in California assuming no storage and a solar multiple SM2. The annual contribution is 40%.

Replacing fossil generation

The capacity factor is the ratio of actual energy supplied to the maximum possible supply by the installed turbines over that period. In Fig. 2, modeled monthly capacity factor (CF) is given for a 50 GW using the 2006 the Californian ISO grid load[9]. The collector model uses and array of SM2, with the array being assumed to only have storage in the thermal mass of the array pipes, fluid, and steam drums. It can be seen that, partially due to the SM2 strategy, the CF is reasonable and the array covers about 40% of the annual California load. This is excellent for a non-storage technology but not enough to allow the technology to generate the majority of power on the grid.

In Fig. 3, the same turbine fleet is now provided with arrays in the SM2, SM3 and SM4 sizes, all with 16 hours of storage. The chart shows the SM3 case to exceed the grid load requirement at all times except in winter, using a peak turbine capacity equal to the peak load of 50 GW, recorded in the early afternoon of July 24, 2006. The 16 hour figure was chosen for use in the graph because it was financially optimal for the SM3 case; many other storage levels were attempted. The correlation with annual load is 92%, without the application of any peaking plant, with only 3% of energy having to be dumped (by turning excess collector capacity off-focus). At SM2, the monthly load is never carried, but zero energy is dumped. At SM4, the entire grid load is carried, but 22% of energy is dumped. The lowest kWh cost case is therefore near SM3, because the turbine operates close to the capacity factor required by the grid, while little energy is dumped.

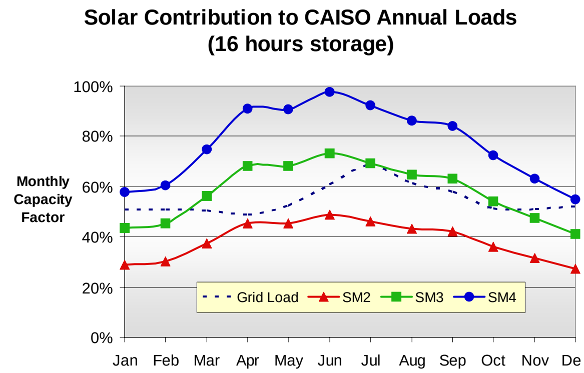

Figure 3. The published load capacity factor (CF) of the 2006 Californian CAISO grid together with the modeled outputs of systems for SM2, SM3, and SM4. All the modeled systems use 16 hours of storage. Hour by hour data in the model has been aggregated into monthly generation system outputs.

In Fig. 4, the model results for the Texas ERCOT[10] grid are given for SM2, SM3, and SM4. Again, 16 hours of storage was assumed. The chart shows the least cost SM3 case to fall short in summer, using a peak turbine capacity equal to the peak load hours of the year. This was 63 GW, recorded in the early afternoon of May 8, 2006. Again, SM3 is best, with a 91% correlation without needing peaking plant.

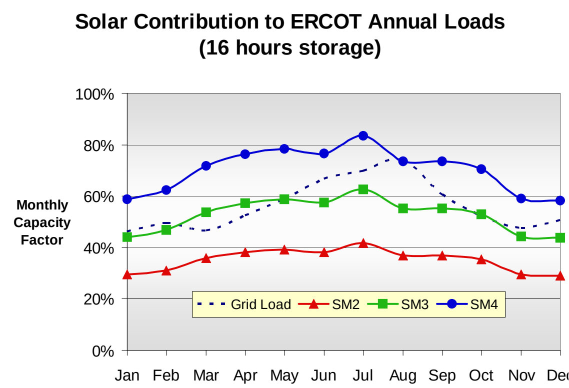

Figure 4. The published load as per Fig. 2 but for the 2006 Texas ERCOT grid. The system is noticeably more peaked in mid-summer than the CAISO, possibly due to air conditioning usage in hot and humid months, but the correlation of SM3 is still excellent at 91% with minimal dumping.

While the high supply fractions are compelling from a regional viewpoint, a more ambitious thought experiment addresses the supply of the entire national grid from the modeled Texas and California solar arrays. Of course, supply of the USA would take place from many southern and western states, but using two distant states like California and Texas is illustrative.

In Fig. 5, the dashed line indicates the 2005 national grid profile scaled to the 108 GW coincident peak of the CAISO and ERCOT. The result – surprisingly - is even closer to the two-state blended solar generation correlation, with 96% of the national annual grid supply accessible to least cost SM3 STE. However, this chart was prepared by using monthly national data, not the hourly data available through CAISO and ERCOT. Nevertheless, there is a close match between the forms of load patterns of Texas, California, and the national grid, suggesting that similar amounts of storage could be used to the same effect. Further, there would be a tendency for extreme local weather events to be averaged out, and there would be hundreds of solar plants available with flexible storage and considerable geographic diversity. For this reason, a result close to or better than that in the California case is not unreasonable.

This close correlation in a country having a severe winter in the northern regions might seem not to be intuitively correct, but the excellent seasonal match at the national level can be better understood if one realizes that winter home heating loads are carried out by non-electrical energy (gas and oil) and that air-conditioning is mostly electrical. This produces a close national load correlation with solar seasonal availability similar to that previously calculated for the warmer states.

The 2005/6 U.S. national grid had a generating capacity of 1067 GW and non-coincident peak load of 789 GW [11]. Based on the current technology, a CLFR with SM3 and storage would require 1.5 square miles for 177 MW, translating a national land requirement equal to 23,418 km^2 or a square with 153 km sides.

Replacing Oil

Recently there has been recent development of lithium ion batteries and supercapacitors[12] that may provide the possibility of fast recharging electric vehicles which would use zero fossil fuel. The electricity for such vehicles would come from the national and state grids, and therefore can be supplied by grid-connected renewable energy with low climate impact.

The annual U.S. figure on 2006 for vehicle emissions has been calculated by the DOE[13] to be 2.0 billion metric tonnes CO_2 equivalent (CO_2e). This is close to the annual US Electricity generation emissions of 2.3 billion metric tonnes CO_2 equivalent (CO_2e). Together this is 4.3 billion tonnes per year.

A Socolow Wedge[14] is a saving of 1 billion tonnes of Carbon emissions per year reduction. Multiplying by 44/12 to convert to tonnes of CO_2e, a single wedge is 3.7 billion tonnes of CO_2e per year. Seven wedges are require to drop the atmosphere to stabilisation of 550 ppm of CO_2e over 50 years, so the potential of removing emissions from the US generation and vehicle fleets is 4.3/(3.7 x 7) x 100 = 17% of the entire global reductions required. The potential in other markets like China, Europe and India is also large.

The U.S. national vehicle fleet-miles travelled were 1.0 x 10^{13} in 2005/6[15]. Battery electric vehicles typically use between 0.17 and 0.37 kWh_e per mile, so for 1.0 x 10^13 miles of vehicular travel the US would need 1.7-3.7 x 10^6 GWh to fully eliminate vehicle emissions from fuel use. In this thought experiment, national solar generation would consequently have to climb by 42% - 91% to accommodate an entirely electrified vehicle fleet. The land area requirement for the supporting CLFR generation plant would climb to between 182 and 211 km on a side.

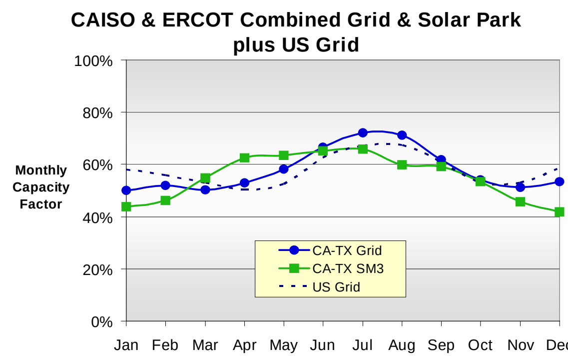

Fig. 5. The effect of blending the grids from Texas and California and using SM3 arrays as in Figures 1 and 2 (solid lines). The national load figure is also shown (dashed line).

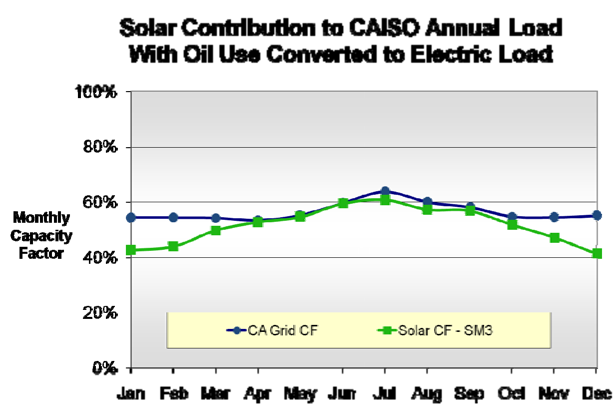

Fig. 6 A SM3 solar fleet in California addressing a grid load which includes the majority of static generation and an electric vehicle fleet. The correlation between solar output and load is 93%.

Superimposed on our electricity load, this would have some implications. Although fast charging will be available, it is likely that much of charging will take place in the home garage, leading to a stronger night load. Because we do not have hourly data for the entire US grid, or a typical charging pattern, we can look at a simple model in which the more extreme effect of placing 91% more generation into one state, California, spreading the charging period over the period between 9 PM and 9 AM. It is likely that technical improvement would drive vehicle efficiency toward the lower end of the range after a decade of manufacture, but the authors ignore this, This model also does not benefit from time zone displacement as would occur in a national model. For both reasons, it can be regarded as a worst case. Fig 6 shows a calculation for California, such that peak generation is now 50 GW x 1.91 = 95.5 GW. It can be seen that the effect on the model correlation is marginal, with the SM3 configuration continuing to be preferred and the correlation slightly improved over the 50 GW California model in Fig. 3 at 93%. This suggests that on a national basis, the correlation will also remain high with a grid load which totally includes the vehicle sector. For more efficient vehicles, the added grid load would be smaller but the correlation similar.

The current cost of a CLFR system is approximately US$3000 per kW; we believe it will drop rapidly to US$1500 per kW within a few years as a result of a numerous technical improvements already identified. At a future estimated cost of $1500 per peak kilowatt, this is ($672 - $1456 billion)/0.93 (the 0.93 because we only supplied 93% of power in the case calculated), or about $723 - $1566 billion in capital investment to provide a grid which supplies the great majority of static and vehicular loads. The current cost of imported oil to the USA at $100 per barrel at an import rate (in 2005/6) of $13.2 million barrels a day is $482 billion per year. The simple payback time in balance of payments by substitution of solar for oil is approximately 1.5 - 3 years. Even at the current cost of the CLFR system, it would remain an attractive investment. This simple economic argument neglects very large benefits to the local environment, which, in addition to global environmental benefits, would include a much cleaner atmosphere in urban areas and the avoidance of associated health costs.

Of course, the installation of transportation generation would not be immediate but would occur gradually. In a somewhat aggressive scenario, if installation were spread over 30 years, then the annual generation replacement cost would be between US$24 and US$52 billion. Each such annual investment would avoid US$48 billion in imported fuel costs *each year for the life of the plant*. This would provide both a large and continuing benefit to the US economy. The primary uncertainties in this calculation are the rate at which pure electric vehicles can be introduced, and the assumed electricity usage per km. However, the payback is so high that only a very great increase in the cost of electric vehicles over fuelled vehicles could reverse the economic benefit.

Discussion

Although it is often said that “solar cannot produce base load electricity”, STE is probably the only currently available technology which *can* be considered for a globally dominant role in the electricity sector over the next 40 years.

Humankind evolved to be most active when the sun was up, with our eyes having been optimized through evolution for the sun’s spectral emission. This is why human activity and energy usage correlates significantly with the energy delivery from direct solar systems. Additional seasonal correlations detected in this paper result from the influence of the national building air-conditioning load, which is greater toward summer months when the sun delivers more direct solar energy to the earth’s surface. We have up to now largely neglected these advantageous correlations when designing power systems technology. The results of this paper suggest that such hourly and seasonal natural correlations with energy output from a solar system are substantially enhanced using storage. An immediate advantage is that load-following solar plant does not need expensive peaking plant backup. It is clear that natural correlations can be used to economic advantage in solar power system design.

The relevance of base load generation as a technical strategy needs to be carefully re-examined. Human activity does not correlate well with base load coal or nuclear output. It should by now be recognized that base load is what coal and nuclear technologies produce, not what is required by society and the environment.

Solar power with storage can take up as much of the grid generation load or vehicle energy load as is desired, and can host other clean energy options by treating them as a negative grid load. A mixture of storage and non-storage renewable options thus appears to be fully self-consistent as an alternative to the present generation mix, with the main co-contributors to STE probably being hydroelectricity and wind.

Conclusions

This paper suggests not only that STE is a energy option of great significance, but that with only 16 hours of storage it has sufficient diurnal and seasonal natural correlation with electricity load to supply the great majority of the US national grid (and by logical extension, those of China and India) over the year, with the hourly solar radiation data including typical cloudy weather patterns. Furthermore, STE can supply much of an electrified transportation market without destroying the natural correlations discussed above. An almost complete elimination of both fossil-fueled generation and oil usage for transportation in the USA appears to be technically feasible. A simple calculation provided in this paper suggests that this option will cost less than continuing to import oil.

Zero emissions technology is required to replace most of current generation by mid-century to meet stringent climate goals. What is now needed to facilitate such a vision is a rethink of the function and form of electricity grid networks, and the inclusion of high capacity factor solar electricity technology in the design of continental electricity systems. The scenarios in this paper are basic and could be much improved with sustained effort at a national and state level. However, the underlying correlations of solar power with societal and environmental needs are clear.

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