SOLAR THERMAL POWER AS THE PLAUSIBLE BASIS OF GRID SUPPLY

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ABSTRACT

The energy system must be producing close to zero emissions by mid-century to meet stringent climate goals. There are many possible clean energy options, but few are ready or able to replace coal and gas as primary electricity supplies. This paper addresses the issue of whether a viable energy system can be based mostly around solar thermal electricity. It is found that, using thermal storage, correlations >90% between hourly grid load data and hourly solar plant performance are easily attained, aggregated as seasonal and annual loads. We also discuss the ability of low cost solar thermal electricity with storage to assist other renewable energy technologies with useful seasonal correlations. The results suggest that both state and national US systems can be largely supplied by direct solar thermal electric systems which are close to market-ready.

1. INTRODUCTION

It is now generally accepted by the scientific community and the general public that global warming caused by human activity is a serious threat to the climate. Recent work along these lines by Hoehne [1] examined the detailed difference between 450 and 400 ppm greenhouse gas equivalent scenarios for 2050. Hoehne concludes that a 450 ppm CO_2 equivalent concentration, accepted by many as a mid-century target, is not a 'safe' option: the risk of serious climate tipping points is not excluded. Thermal runaway events within the uncertainty of 2001 and 2007 IPCC estimations of global warming may permit average temperature rises as high as 6 degrees globally, and higher still over land areas [2,3,4,5,6]. Such an eventuality could lead to massive species extinctions and land inundation.

According to Hoenhe, a preferred 400 ppm scenario implies an almost complete abandonment of fossil fuel, excepting a little natural gas burned at combined cycle efficiency (~50%), unless a practical carbon sequestration solution is developed. Even a 450 ppm scenario implies the abandonment of coal in developed countries, again unless cost-effective carbon sequestration appears. The inescapable conclusion is that technologies that operate with very low or zero net emissions are needed under both scenarios as the great majority of the new generating system. Simple improvements to the efficiency of generation are too little, too late.

This paper presents basic solar thermal electricity as the most plausible primary means to nearly eliminate contributions to global warming from electricity generation by mid-century. By association, such technology could also eliminate vehicle and building heating emissions using electric technology such as plug-in electric vehicles and reverse cycle air conditioners. It would thus act to decrease consumption of not only of coal, but of oil and natural gas.

Using the California and Texas electricity grids as the basis for illustrative regional scenarios, the paper then offers a further national thought experiment with clear continental implications.

3. SOLAR THERMAL ELECTRICITY

The sun is a much larger practical energy resource than any non-direct solar resource. Both photovoltaic technology (PV) and solar thermal electricity (STE) utilize this resource. STE uses a field of solar reflectors to run a heat engine such as a Rankine or Brayton cycle. In this paper, we avoid use of the more common but less specific term Concentrating Solar Power (CSP) because CSP also includes PV concentrators, which do not have the crucial storage benefits of STE.

STE is a proven concept. It has been successfully demonstrated in the Californian desert for two decades using commercial **parabolic trough technology**[7] 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% [7], due primarily to O&M requirements of the conventional steam turbine used. **Central tower 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[7]. A third option recently developed commercially is the **Compact Linear Fresnel Reflector (CLFR)** system (Fig. 1), which is a linear system using long steam pipe receivers on towers, illuminated by long heliostats below [8,9].

Fig. 1: A recently installed CLFR array segment in Australia. Tracking linear reflectors focus solar energy on elevated boiler tubes to produce steam.

Unlike PV, STE can use low cost energy storage in artificial thermal reservoirs. Oil storage was successfully demonstrated commercially in the mid 1980's[10] and molten salt is being commercialized in parabolic trough plants in Spain[11]. Very low cost water-based thermal storage is expected to be commercialized within two years[9]. In designs using storage and no fuel, there is long term immunity from fuel cost rises.

To produce today's total annual US electricity generation would require land equivalent to a square about 145 km on a side using advanced CLFR technology. China and India have similar desert regions, and could power their own grids from this resource. Europe has access to North Africa and Iberia. It is thus relevant to ask the question: can this enormous primary source of energy – direct solar energy - really become the backbone of US and global grid generation?

PV uses the same direct solar resource as STE but cannot become this bedrock of supply. Both PV and wind are currently limited by lack of low cost storage systems, so that variations in sun and wind are transmitted into the grid and need to be balanced by other technologies; wind, for example, is normally said to be limited to below 20%, as a regional supply.

In contrast, because of the ability of STE to use low cost thermal energy storage between the solar array and the turbine, very high grid supply fractions are possible without auxiliary peaking systems.

3. CALCULATION OF GRID SUPPLY FRACTIONS

The STE approach in this paper uses US grid examples and presumes costs and performance similar to the newest CLFR versions built by Ausra Inc. (see Fig. 1). The solar data used is Typical Meteorological Year (TMY2)[12] which uses hourly data from real days arranged in a year which reproduces typical weather patterns. The data on the Californian grid usage is based upon hour by hour grid load data from California (CAISO)[13] and Texas (ERCOT)[14]. The modeled turbine fleet capacity was sized to the 2006 peak annual load of each grid, with variations to both the solar multiple and thermal storage capacity to determine optimum sizing of array and storage.

The solar multiple is the ratio of actual 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. It does not provide seasonal storage.

TABLE 1: ASSUMPTIONS IN MODEL

Array installed cost	US $3.25/Watt at SM3
Financing	20 year taxable (LIBOR index + 250 bp)
After Tax ROE	12%
Turbine	740 MW saturated steam
Storage	16 hours

The standard project financial model of Ausra is used to calculate the annual fraction of state electricity which can be supplied to California and Texas. Ausra's project model is adapted to the US market, and the assumptions in it are given in Table 1. This analysis includes very standard financial assumptions, such as 20-year depreciation and no tax benefits such as those available in the US today. Thus our cost conclusions can be considered true "cash" costs of large scale STE in US$ and should be transferable worldwide. Costs are not strictly required for a discussion of resource potential in grid applications, and prices that emerge are subject to the assumptions used.

In Fig. 2, modeled monthly capacity factors (CF) are given for the Californian grid load and for SM2, SM3, and SM4. The capacity factor is the ratio of supplied energy to the maximum possible supply by the installed turbines over that period. 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.

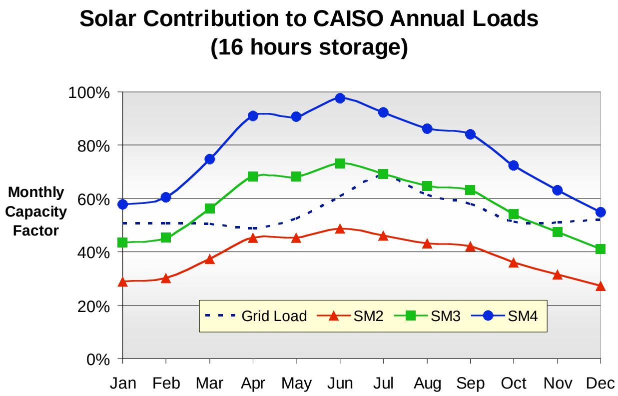

Fig 2: The published load capacity factor (CF) of the 2006 CAISO grid together with the modeled outputs of systems for SM2, SM3, and SM4. All the modeled systems use 16 hours of storage. Hour by hour data in the model has been aggregated into monthly generation system outputs.

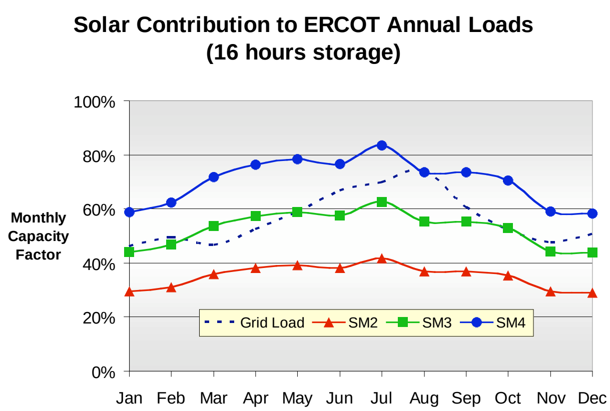

Fig 3: The published load as per Fig. 2 but for the 2006 Texas ERCOT grid. The system is noticeably more peaked in mid-summer than the CAISO, possibly due to air conditioning usage in hot and humid months.

In Fig. 3, the model results for the Texas ERCOT 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.

There are differences between California and Texas in the times of year when excesses or deficits in power occur. This suggests, as a thought experiment, creation of a simple scenario in which these two grids are interconnected.

In Fig. 4, a 'blended California/Texas grid is shown with a blended output from the SM3 arrays in each State. Hourly grid loads are summed to get coincident peak information and solar DNI is averaged to simulate the combined solar generating fleet. This results in an increase in solar fraction of the grid supply, because local peaks and troughs in load and supply are averaged between two States.

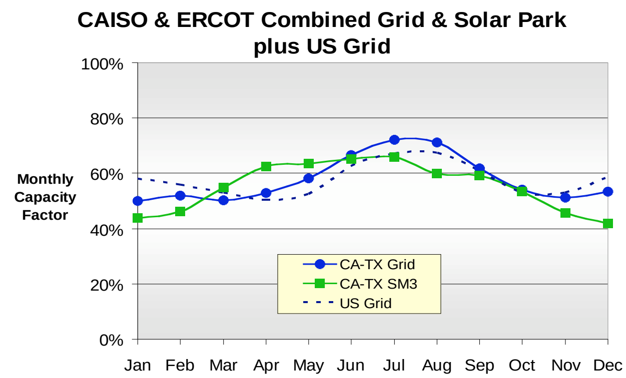

Fig 4: The effect of blending the grids from Texas and California and using SM3 arrays as in Figures 1 and 2 (solid lines). The national load figure is also shown (dashed line).

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. In Fig. 4, the dashed line indicates the 2005 national grid profile scaled to the 108 GW coincident peak of the CAISO and ERCOT. The result is even closer to the two-state blended solar generation correlation, with 96% of the national annual grid supply accessible to least cost STE.

Table 2 shows the fraction of grid electricity supplied by the various solar multiples and also discarded (dumped) energy caused by turning some of the solar field off-focus when the grid load is exceeded. This is shown for the blended state case, in which 92% of the blended state annual load can be supplied by the cheapest array option, SM3. The explanation for the cost minimum is as follows: below SM3, the turbines produce less output per day because there is less array per turbine, increasing kWh cost; above SM3, periods of oversupply from the arrays occur (mainly in summer) which cause energy to be dumped from the system, increasing collector cost per unit of electricity produced. There is a 7.7% cost per kWh penalty for attempting to obtain the last 8% of grid load due to increased dumped solar. This could be supplied by other clean resources such as hydro-electricity and wind if they are less expensive. Otherwise, the increase in cost is tolerable.

TABLE 2: RESULTS OF BLENDED GRID SCENARIO

	Grid Load Served	Dumped Energy	Levelized Cost of Energy ($/kWh)
Solar Multiple			
4	100%	22%	$0.084
3	92%	3%	$0.078
2	63%	0%	$0.106

4. DISCUSSION

The results show that the 'rough' intrinsic daily solar correlation with grid load can be greatly improved using modest thermal storage.

A second result is that the seasonal variations in grid load in the two example 'high-solar' states are closely matched by solar system output by optimizing the ratio of array size to turbine size (allowing some dumping in peak solar months). A solar multiple of 3 and 16 hours storage was the lowest cost per kWh.

A third result is that the modeled single solar-based technology with storage can deliver 92% of the blended grid load of Texas and California in the SM3 configuration. Texas and California were examples used because data was readily available, but the results should apply to many other high-solar resource states.

More surprising still is the fourth result, that the national grid match at 96% was better than the two-state blended match, also using SM3 and 16 hours of storage. 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.

The authors lacked the hourly data to calculate how well the national correlation persists on an hourly calculated basis. However, the overall monthly shape of the load curves seem broadly similar between the blended states and the national grid, 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.

However, looking forward to mid-century, the elimination of most oil and gas emissions also becomes an important goal. This implies that the clean electricity grid may acquire the building heating and transport markets.

By mid-century, winter heating loads now performed by oil and gas would have to be either eliminated through passive solar construction or included in the grid load by using efficient electrically powered reverse cycle heating. In addressing this potential problem, there exists another helpful renewable electricity correlation with load. In the case of the northern wind resource, the wind peaks strongly in winter[15] and is seasonally well-correlated to the national building heating load currently supplied outside of the grid. This correlation will be better elaborated in the future, but available variables including plant geographic locations and time zones should allow fine tuning of load matching on an hourly basis. Perhaps more importantly, the storage of both STE and hydroelectricity can diminish or increase in output as the wind generation rises or falls. This brings up an important point; a large on-grid fraction of STE with storage can host other clean technologies lacking storage, such as wind and PV. No mention of improved building efficiency was assumed, but this could also substantially reduce the building load.

Electric plug-in vehicle propulsion may also have to be included in the future grid load, but this is a flat seasonal (potential) grid load and would not seriously upset the overall national correlation with solar.

It is possible that a rare long-lasting cloud event could cause a state-wide shut down of generation very occasionally. A nationwide HVDC grid system would alleviate the impact of such regional difficulties. Prices could also be determined to rise during extreme cloud events to discourage demand. However, once one realizes that fossil fuel usage must be restricted to very low levels by 2050, it may also be possible to allocate any vestigial fossil fuel "budget" to the very infrequent emergency heating of STE storage systems, using the existing gas grid or oil storage tanks. If fossil fuels become totally banned, biogas or biodiesel could be stockpiled for this purpose.

Some experts insist that low cost 'clean' coal and nuclear are the solutions and that renewable energy cannot do the job. Coal fired generation with carbon sequestration needs Integrated Gasification Combined Cycle (IGCC), a type of power plant that gasifies coal into synthetic gas to power a gas turbine. In April 2007, Minnesota's Office of

Administrative Hearings rejected the proposed Mesaba IGCC plant, saying that NOx and mercury emissions are not improved over a conventional coal plant with modern pollution controls[16], that the basic plant would cost 9-11 cents per kWh, and that capturing and transporting the carbon would add at least 5 cents per kWh[17]. This is a significantly higher cost than STE plants now being contracted. Sequestered coal is also more polluting, and the sequestration technology is unproven.

Nuclear fission supplies about 17% of global electricity generation. Economically recoverable uranium fuel resources are just 2.8 million tonnes and would last just 42 years at the current level of uranium consumption, calculated to be 67,000 tonnes per year[18]. Unless nuclear fuel costs and energy investment are dramatically increased, there is simply not enough nuclear fuel to carry on after mid-century with current technology and there are serious downsides in proliferation and decommissioning[19]. Fuel resources can be extended with breeder technology, at the unacceptable price of increased vulnerability to terrorism, according to a major MIT study[20].

There are several new clean technology suggestions under development for grid usage, such as deep geothermal generation, but they are unproven and we have limited time for their deployment. The only large scale option with a sufficient resource, adequate lead time, rapid installation, and a 24 hour delivery capability is STE. Although Parabolic Trough plants are expected to drop to competitive prices by 2020[7], CLFR plants will be built by 2010 with generation below peaking gas prices in the USA and will drop to coal generation prices soon after.

Of course, there is a necessity for continued development: in particular, STE needs more field proof of storage systems. This is expected to be complete by 2010 for Andasol molten salt and Ausra water-based systems, but it would be incorrect to think that this is a major hurdle. These storage systems are much simpler than the technology required for effective coal sequestration or nuclear reprocessing and decommissioning.

5. SUMMARY

Although it is often said that "solar cannot produce base load electricity", it should now be recognized that base load is what coal and nuclear technologies produce, not what is required by society. Because humankind evolved to be most active when the sun was up, human activity and energy usage correlates significantly with the delivery from direct solar systems. Human activity does not correlate with base load coal or nuclear on a daily basis. *Load-following* clean technologies are what we should be seeking. Coal and nuclear could be designed to be load-following, but the industry clearly thinks that the cost would be so high that they would rather use expensive gas peaking plants.

This paper suggests not only that STE is a energy option of great significance, but it has sufficient seasonal correlation 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 at its optimal price. Indeed, STE is probably the only technology which *can* be considered for such a dominant role over the next 40 years. It can also accommodate and assist non-storage technologies such as PV or wind where these offer price or seasonal load correlation benefits.

There are many ancillary benefits to STE. There are no waste issues of significance and the technology is very safe. Rapid construction has been demonstrated. It is better distributed around the grid network; many widely distributed sites can achieve high fleet reliability. It is potentially lower in cost than coal or nuclear, and the STE scenario in this paper eliminates expensive peaking plants as an added system benefit of load-following.

STE is also well distributed internationally, and would decrease international unrest by allowing most countries to source adequate electricity and vehicle energy from within their region or borders. The USA is particularly well placed to deliver 100% of supply from renewable energy, much of it solar.

Zero emissions technology is required to replace most of current generation by mid-century to meet stringent climate goals. What is now required as a climate safety, economic, and security imperative 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.

6. ACKNOWLEDGMENTS

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