RUNNING THE USA FROM WIND AND SOLAR

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1. Introduction

This paper investigates the proposition that wind and solar energy can run the entire continental US electricity system without blackouts. The aim of this paper is to employ hour by hour datasets for the entire year to establish the amount of wind power, solar concentrating solar power and electricity storage that would be required to reliably meet the entire 2006 electricity load of the continental United States. The United States was selected for the modelling study because it is a large-sized system with many generation sites for good statistics, has a large range of weather regions, has very good load data from past years, and is a major emitter of greenhouse gases. This paper is an individual effort of the authors and has no connection to former or current employers.

The need for the paper developed from an examination of solar energy powering California and the full United States (Mills and Morgan, 2007, Mills and Morgan, 2008). This paper showed that more than 90% of the electricity sector could be powered by solar power with sufficient thermal storage, but the coverage left extensive times when blackouts might occur unless large auxiliary, probably polluting, generating systems were present. Even if the electricity were unavailable only 5% of the time, that would amount to 18 days a year of potential balckout. Mills and Morgan (2008) suggested that there might be synergy between wind and solar power allowing improved coverage of diurnal and seasonal energy loads in the United States. However, the load coverage of their papers did not extend beyond the existing electricity sector, leaving large sectors of the energy economy with a fossil fuel basis.

The electricity supply was calculated on an hour-by-hour basis for the example year 2006, using US Government energy load data and NREL solar and wind weather data for load match modelling. The basic technologies assumed for the modelled systems are already available, and large technical advances are not required to produce a functioning national energy system without blackouts, but the solar system design is adapted to peaking. The system uses no baseload, but may use less than 2% backup using gas-powered combustion turbines to reduce capital investment, although fully 100% solar + wind solutions were found.

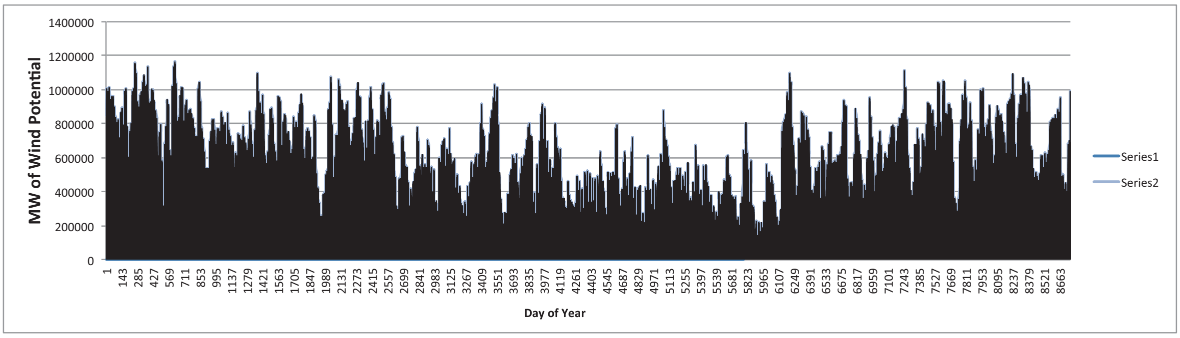
2. Study Assumptions

We confined our analysis into a scenario that only includes thermal energy storage for concentrating solar thermal plants. Low cost electrical storage technology might someday allow wind or PV technologies to have a more dominant role in system load matching, but its development cannot be assumed. Instead of an average year or solar Typical Meteorological Year (TMY), we used combined solar and wind weather data from a real year to reflect solar/wind weather relationships that might be lost in a TMY model. We chose the year 2006 because detailed load and weather data for hourly resource analysis were available. As an important input for this report, we chose solar and wind production sites within the U.S. that are representative of likely production areas, and have acquired National Renewable Energy Laboratory (NREL) and National Aeronautics and Space Administration (NASA) sourced hourly resource data that enabled us to create models of hourly solar and wind generation for 2006. We created a separate model to correlate solar and wind availability with a hourly national electricity load calculated from primary Federal Energy Regulatory Commission (FERC) data. It is important that the load can be served by any generator on the grid that is available.

3. Wind Resource Database

Two NREL 2006 wind datasets called the Eastern Wind Integration and Transmission Study (EWITS, 2011) and a corresponding Western Wind Integration and Solar Transmission (WWSIS, 2011) study for the west were acquired by the authors and combined into a national hour-by-hour national database for that year. The authors synthesised a full database for 2006, and it was found that around half the accessible resource comes from the 8 states of Wyoming, New Mexico, Colorado, Minnesota, Nebraska, Montana, Texas, and California and only about 6% from offshore sites. In Fig. 1, a graph of modeled wind output for the continental USA using 2006 wind data shows a large degree of seasonal fluctuation with a strong bias toward winter generation and a winter peak of 1.02 TW(e) of coincident generator output. In summer the entire wind fleet can drop as low as 67 GW(e). As we had hoped, the relationship between solar and wind is symbiotic and higher wind speeds in winter and at night are supported by higher summer and daytime solar availability. The average wind capacity factor (CF) is 35.7%.

Fig. 1. Wind generation output for the USA in 2006. It can be seen that there are extremes of output between summer and winter. The wind output is prone to fluctuations between 0.067 and 1.02 TW(e).



4. Solar Generation Technology and Modelling

The term "CSP" (Concentrating Solar Power) is often used for technologies using optical concentration, but this term includes both CPV (Concentrating photovoltaic) and CST (Concentrating Solar Thermal), and these need to be clearly distinguished in this paper because CPV is not available as a technology with low cost storage. Consequently, this study only analyses CST.

CST systems use concentrating mirrors or lenses to create high temperatures for generation, and most use glass mirror for its low cost, structural utility, durability, excellent surface smoothness, and high reflectivity. Current line-focus systems deliver between 270° and 400°C and two-axis tracking systems between about 450°C and 1000°C. The industry is developing line-focus systems and tower systems at 550°C and contemplating supercritical central tower systems at 700°C. Parabolic line-focus troughs have been the primary CST technology used commercially so far, and operate close to 400°C in the collector loop. However, it is not clear which technology will prevail in the future, and mixtures of these technologies - for example a line-focus system with a tower superheater - may also be also possible.

Unlike current utility grade PV technology, CST has the unique ability to use any of direct solar, storage or backup fuel to power the same turbine depending on load and solar availability.solar unavailability. The backup fuel can be a fossil fuel like natural gas, or a renewable fuel like solar-produced hydrogen. If low-cost, high round trip efficiency electrical storage were ever developed for PV, it would offer similar grid and national generation matching benefits as the CST storage systems, but not the use of backup fuel. If there is an oversupply of energy and the storage is full, then dumping would take place. 'Dumping' simply means turning solar mirrors off focus or shutting down wind generators.

The highest solar radiation sites for CST generation are concentrated around the south and south-west of the USA. This study uses generation locations in Daggett and Ivanpah California; Las Vegas, Nevada; Palo Verde, Arizona; El Paso Texas; the Colorado San Luis Valley where solar peaks strongly in summer; and los Lunas, New Mexico. The direct normal incidence (DNI) solar radiation data for these locations were provided by Clean Power Research (Solaranywhere, 2011) and were based on NASA and NREL satellite data from 2006 assisted by correlations with ground-based measurements formulated by Cebecauer et al (2010). These seven sites would represent the variations in seasonal solar output likely in good locations at different latitudes and the output was divided equally between them; it would be possible, but perhaps politically impractical, to allocate solar arrays in such a way to improve the overall match to annual loads.

5. Electricity Load Database

National hourly electric load data for the reference year 2006 was downloaded from the Federal Regulatory Commission's online database (FERC, 2009), which includes all electric transmitting utilities operating balancing authority areas and planning areas with annual peak demand over 200 MW. The output of each of the 127 regions is referenced to a time zone and were matched in the UTC time zone. The FERC databases were examined in detail and compared to overall national output figures provided by the EIA (2010). It was discovered that all of the FERC 714 loads total up to 4825 TWh, while the EIA data for domestic generation + imports for 2006 is 4107 TWh, for a discrepancy of 17.5%. The principle reason for the discrepancy between the FERC and EIA data is load overlap, and thus double-counting, between the entities that submit FERC 714 data. An effort to remove this double-counting was accomplished by examining the submissions in more detail and a revised dataset was formed with total usage of 4227 TWh, reducing the discrepancy to a more reasonable 2.9% difference. There was not enough detailed information provided to go further, but is possible that there were additional double-counts in the original data, so the authors opted to use the 2006 EIA figure of 4107 TWh as the accepted figure, and scaled it to match the hourly profile obtained in the recalculated 4227 TWh database. This means there is a potential underestimate of between zero and 2.9% in the 2006 electricity usage data. If that exists, it would not significantly affect the realisation of a 100% match, since additional wind and solar resources could be deployed to cover it. It was more important that the seasonal variation be correct when matching the load with wind and solar. A small amount of Jan 1st 2006 data missing in the FERC files and was replaced with plausible numbers.

Fig. 2 shows the calculated variations in the 2006 national electricity load with the lower bound of the curve composed of the night-time minima and the upper bound as the day-time maxima. Weekly "sawtooth" patterns are visible due to reduced usage on weekends. The electric load peaks in the summer, like the seasonal solar peak, and the variation between day and night increases in summer due to the daytime air conditioning load. The annual consumption showed a peak of 774 GW and a minimum at 289 GW. For an annual electrical load of 4107 TWh, the grid capacity factor (CF) is 60.6% referenced to the peak load. Referenced to the nameplate peak generating capacity of 1075 GW, the generation CF drops to 43.6%.

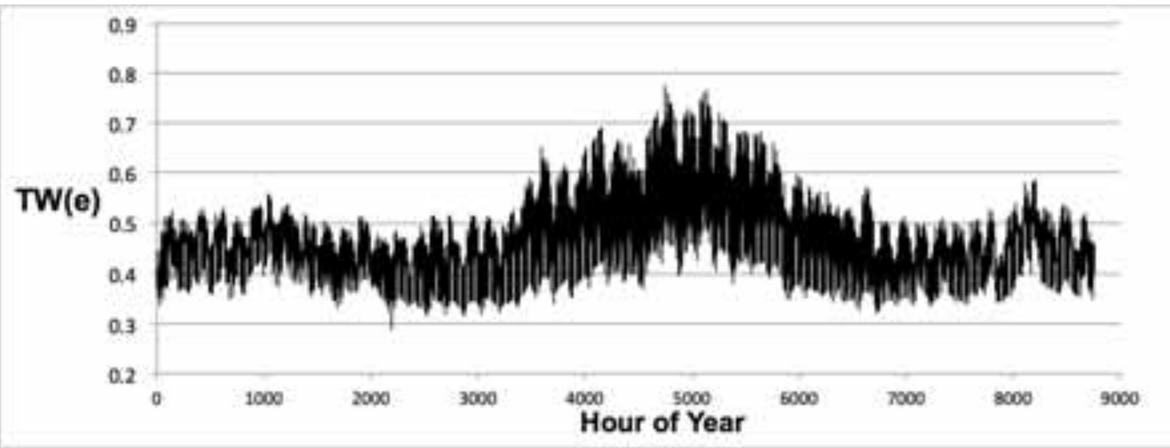


Fig. 2. Calculated continental US electricity load for 2006 in terms of TW(e) vs hour of the year. The underside of the characteristic shows minimum values which lie mostly above 3.1 TW(e).

6. Modelling Results for a Wind/Solar Supply System for the US 2006 Electricity Load

In this paper, load matching is calculated using a model developed as a simple generic load-matching algorithm that would approximate the behaviour of many individual generators. The solar fleet was assumed to be freely dispatchable to the extent permitted by the thermal storage in the system. The wind component was assumed to be uncontrolled except for shut-down. The algorithm will be able to be accessed a full published paper in preparation.

Table 1 shows the results of load matching with wind and solar fleets are designed with a total available annual electricity output of 125% of the annual load. *Energy redundancy* is defined here as the excess potential annual energy delivery potential of the systems as a percentage of the annual load. Thus, the combined wind and solar system has 25% redundancy. Without storage, a predominance of wind gives the best result because of the lack of solar input at night, but with storage, a predominance of solar capacity achieves 99.99% load coverage with 18 hours or greater of solar thermal storage. With no storage, such near-complete coverage cannot be attained without an additional alternative backup system or vastly increased redundancy. This would also be true of PV systems without storage.

For the case of 99.99% coverage, one would expect blackouts for 0.01% of 8760 hours per year, or 53 minutes per year. This is about 25% of the accepted dropout rate for the current grid system of 214 minutes or 3.57 hours (Apt, 2006), but the latter also includes grid faults. The solar/wind system assumptions look only at matching the load to output from 100% functioning plants. However, high modularity in wind and solar plants means that unanticipated failures of individual wind turbines and solar mirrors, two of the most costly items, should not have a significant dropout effect. The availability of the two-decade-old Californian SEGS CST plants has been typically around 99.5% in recent years (Cable, 2001) with major scheduled maintenance done in mid-winter when seasonal output is low. Modern individual wind generators have an availability of more than 98% (AWEA, 2011). In addition, although 25% redundancy is present to offset joint solar and wind resource lows, it will also greatly help with system availability because extra plant would almost always be available; any fault-based or scheduled maintenance unavailability would have to coincide with infrequent resource lows when capacity is fully used to have a blackout effect. A similar blackout frequency, however, would be still attributable to transmission breakdown. Although the generator reliability of this modular, redundant system should be comparable to or better to the current system, backup options offering greater security will be discussed later in the paper.

Tab. 1: Percentage of 2006 FERC load coverage from combined wind and solar of 25% redundancy according to relative fraction of wind and solar potential, and hours of solar thermal storage. The case with 78.8% solar and 46.3% wind shows the best match of 99.99% for a given storage capacity with 18 hours of storage in the solar fleet.

	Solar Installed (GW)	Wind Installed (GW)	Hours of Storage										
			0	2	4	6	8	10	12	14	16	18	20
Solar = 46.3%, Wind = 78.8%	1159.18	1034.43	83.24%	93.72%	96.03%	96.47%	96.66%	96.74%	96.79%	96.85%	96.90%	96.96%	97.01%
Solar = 62.5%, Wind = 62.5%	1564.76	820.46	76.76%	94.25%	97.96%	98.50%	98.80%	98.96%	99.05%	99.12%	99.19%	99.27%	99.33%
Solar = 78.8%, Wind = 46.3%	1972.85	607.79	67.31%	94.34%	98.82%	99.23%	99.49%	99.67%	99.80%	99.89%	99.97%	99.99%	99.99%
Solar = 95.%, Wind = 30.%	2378.44	393.82	56.48%	93.15%	98.00%	98.37%	98.49%	98.60%	98.71%	98.82%	98.92%	99.03%	99.13%

For the best case in Table 1, the wind fleet must be capable of producing 0.463*4107 TWh(e) = 1902 TWh(e) per year, about 40% of the potential annual USA wind generation of 4756 TWh(e) calculated from NREL data. The total installed peak wind fleet size is 608 TWp(e), and the wind capacity factor is 36.0%. If we assume we use all of the wind 1902 TWh(e) available without dumping, this leaves 2205 TWh(e) to be supplied by solar. The solar capacity is 1973 GWp(e), so the minimum solar capacity factor is 10.2%. However, this is not the only scenario, for solar could be used to replace wind in periods of energy abundance, when storage systems were full. However, if, as one example, the dumped energy were shared equally wind and solar, then the capacity factor (CF) of solar would be 15.8% and that of wind 26.1%. The matching models used make no decision as to whether available wind or solar electricity is dumped. Conventional generation also incorporates significant redundancy. The total *peak capacity* redundancy required to cover failures and maintenance of the conventional generation system was 39% in 2006.

Although the 99.99% result is excellent, is 100% load coverage possible? One obvious way is to increase the redundancy of available generation plant. Table 2 shows the effect of enlarging the wind and solar fleet to 35% redundancy. This successfully achieves 100% annual coverage using 10 hours of thermal storage, and zero fossil fuel usage. The available output before dumping from solar is equal to 83.8% of load, and that from wind equal to 51.2% of load. Load coverage for all 8760 hours is an important result that many would be surprised to see emerge from two highly variable output generation resources.

Tab. 2: Percentage of 2006 FERC load coverage from combined wind and solar of 35% redundancy according to relative fraction of wind and solar potential, and hours of solar thermal storage. The case with 83.8% solar and 51.2% wind achieves 100% for the lowest storage capacity with 10 hours of storage in the solar fleet.

	Solar Installed (GW)	Wind Installed (GW)	Hours of Storage										
			0	2	4	6	8	10	12	14	16	18	20
Solar = 51.2%, Wind = 83.8%	1281.85	1100.07	84.83%	95.37%	96.31%	98.31%	98.57%	98.68%	98.73%	98.79%	98.85%	98.90%	98.96%
Solar = 67.5%, Wind = 67.5%	1689.95	886.09	79.16%	95.89%	99.11%	99.67%	99.82%	99.90%	99.98%	100.00%	100.00%	100.00%	100.00%
Solar = 83.8%, Wind = 51.2%	2098.04	672.12	70.50%	96.19%	99.49%	99.83%	99.94%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Solar = 100.%, Wind = 35.%	2503.62	459.46	59.89%	95.90%	99.02%	99.22%	99.34%	99.46%	99.57%	99.69%	99.80%	99.92%	99.97%

In Table 2, the capital cost of the solar and wind fleets (excepting storage) has been raised by 8% from the 25% redundancy case in Table 1, but required storage size has been reduced from 18 to 10 hours. The best coverage with lowest storage in Table 2 uses a solar component of 2098 GW and has a maximum solar CF of 18.7% before any dumping. This is lower than current parabolic trough non-storage plants of about 25% CF, and much lower than trough storage plants like Solana, a 250 MW parabolic trough plant with molten salt storage being built in Arizona with a 41% CF (Greentech, 2010).

The low CF optimized ‘solar peaker’ fields in Table 1 and 2 are quite unlike current systems, yet they emerge naturally from the optimization. While wind generators are standard in our simulation, the *solar plant design is greatly influenced by the presence of wind as the only generation partner.* The turbine is made larger relative to the field than a normal daytime non-storage plant and can handle large variations in wind output. To construct a 'solar peaking plant' in Table 4, we retain the conventional power block but reduce the relative field size and cost to 18.7/25 (about 75%) of the daytime trough non-storage plant value, and add several hours of storage. The total peak capacity of wind and solar is 2099+672=2771 GW compared to the 1075 GW of conventional plant in 2006. Since there is little or no fuel in the solar/wind mix, any cost comparisons must be carried out with fuel and O&M included, and a second paper involving cost comparisons and additional detail is being prepared for publication.

7. Backup options allowing minimal solar-wind fleet size and cost.

CST systems below 100% would require a backup system added to the cost. Steam turbines installed in the CST plants are under-utilised at periods of low solar availability. When there is a load-matching deficit, these would need only fuel and a combustor/boiler to provide the required thermal energy to the existing turbines to match the load. This has been used for supplementary energy with CST plants in California since the 1980s, when the SEGS plants used about 25% natural gas, a much higher backup figure than proposed in this paper. In the following, the different fuel options are discussed.

7.1 Backup using natural gas fired boiler with a solar plant

Gas-fired boilers with steam turbines can reach efficiencies of about 34% (Natural Gas Supply Association, 2011). Using such boilers with existing solar turbines would not incur a significant backup fuel cost or pollution load because the electricity deficit is so small. For example, by reducing the thermal storage to 6 hours in Table 2, the coverage is reduced to 98.3%. The 1.7% of electricity required to meet the intended deficit would need demand thermal energy of 0.017/.34 x 4107 TWh(e) = 209 TWh(th), about 3.4% of the natural gas used in generation in 2006 in the USA. Use of a 25% redundancy solar plant with 6 hours of storage rather than a 35% redundancy plant with 10 hours of storage reduces wind/solar plant cost by 7.4%, along with an additional 40% savings in storage tanks and media.

7.2 Separately located natural gas combustion turbines

Modern gas turbines have capital costs of $675-$1575 per kWp(e)(Parsons Brinckerhoff, 2008). This is a much greater additional capital cost than for auxiliary combustor/boilers for the solar plants, although gas usage would be smaller because the efficiency of gas turbines is above 37%. It makes much more sense to use the already capitalised solar turbines.

7.3 Biofuel or liquid fuel backup

This is similar to option 7.1 except using biomass for firing. Unless there is a pipeline or relatively high frequency tanker truck supply available, a large storage tank may also be needed. This could thus present a less attractive option than NG, which could use pipeline natural gas. The biomass option has very low cycle emissions compared to gas if properly managed.

7.4 Backup using combusted hydrogen created from dumped electricity

The authors considered taking otherwise dumped electrical energy in low demand periods, dissociating hydrogen from water at about 78% efficiency, and combusting it option 7.1 but without CO_2 impact. The H_2 gas is compressed and stored under high pressure in thick-walled tanks. The turnaround efficiency is only 0.78 x 0.34 = 27%, but the electricity supply is essentially free. The cost of backup supply is therefore based largely on capital costs for tanks (very high), dissociators, and the combustor/boiler itself. This will be discussed further at the end of the paper.

8. Powering the Full US Economy

The electricity sector is only one of the energy sectors that contribute to global pollution. In the USA, many energy sectors such as transportation, industrial heat, and building heating were not majority-supplied by electricity in 2006, but rather by carbon-emitting fossil fuels such as natural gas and petroleum. Zeroing emissions must include a means of decreasing carbon emissions from these markets also. The electricity grid is likely to be the most comprehensive way to distribute sun and wind energy. In the following, we examine whether the same solar and wind approach can carry the whole energy load as it existed in the USA in 2006.

Thermal and transportation load electrification is not only possible, but in many cases already underway for reasons of cost or practicality. The connection of vehicular or thermal loads to the electricity grid can be accomplished through mostly well-understood technical changes to vehicles and heating equipment. Often, the cost of expensive electricity is at least partly compensated by reductions in total energy usage. For example, electric cars and heat pumps require only a modest fraction of the kilowatt-hours of their gasoline and natural gas equivalents for the same tasks, and the running costs and pollution of these systems are often lower. In the following, the additional energy use sectors are discussed and modelled as if they were electrically powered.

9. Electrified Thermal Loads

9.1 Residential Electrification

Total non-electrical annual energy consumption for each fuel was obtained for the year 2006 from the U.S. Energy Information Administration (EIA, 2007) by sector. Table 3 shows residential sector estimates of TWh of non-electricity load for various fuels used in the residential sector in 2006, plus an estimate of current usage efficiency, and an estimate of the efficiency if the load were electrified using up-to-date appliances. This comprises 91% space heating and water heating before electrification and 80% after electrification, so load behaviour remains dominated by these two loads. Building heating and water heating are low temperature applications that can utilise already commercial air source (DOE, 2011) or geothermal (DOE, 2011) heat pump technology to use electricity efficiently. They are increasingly popular due to low running costs, and reverse cycle types also provide air conditioning in the summer.

Tab. 3: Calculation of annual TWh(th) required for the electrified residential sector. 1 Quad equals 293.07 TWh of energy[11].

2006 Residential Sector Data	Quads Thermal	Efficiency before electrification	COP or efficiency after electrification
Natural Gas			
Space Heating	3.1536	0.80	Variable
Water Heating	1.126	0.62	Variable
Cooking	0.22	0.40	0.90
Clothes Dryers	0.07	0.90	0.50
Other Uses	0.04	0.80	2.00
Distillate Oil			
Space Heating	0.8	0.80	Variable
Water Heating	0.11	0.62	Variable
Liquefied Petroleum Gases			
Space Heating	0.28	0.80	Variable
Water Heating	0.05	0.62	Variable
Cooking	0.03	0.40	0.90
Other Uses	0.17	0.80	2.00
Wood Fuel Stoves	0.4	0.8	Variable
Kerosene and Coal	0.11	0.8	Variable
Total Residential	6.55		
Total Quads	6.56		
Total TWh(th)	1922		

The efficiency of current gas furnaces is about 80% using natural gas (Energy Star, 2009a) and this is assumed for other current fuels LPG and distillate oil. Using heat pumps, most water and air heating would be done in the winter when their efficiency is lowest, but much higher than direct heating, with a COP can be assumed to be 2 in mid-winter and 4 in peak summer. Space heating load drops to near zero in summer and peaks strongly in winter; it is assumed to be constant in Jan/Feb/Mar and then decline to zero in August, rising again to the January peak value. Diurnally, it is assumed in a simple model to be at 50% peak value between 9AM and 5PM, and 100% of peak value at other times.

Water heating efficiency would increase from 62% for natural gas systems (Energy Star, 2009b) to a coefficient of performance of 2-4 using a heat pump water heater (EIA,2009). The water heating load can vary, peaking in winter when inlet water temperature is lower coming from pipes in the chilled ground. UK data for the seasonal temperature pattern for the soil suggests that for northern hemisphere regions, August is the peak air temperature month and the soil is coldest from January to March (EEBPH,2004). The water heating load is the highest in these months and starts to drop in April. Water heating energy is used while people are awake between 6AM and 11PM, so the load is assumed to be at 100% of peak daily value between those hours and zero at other times.

Cooking is assumed supplied by electricity using relatively new induction heating technology. Induction cooking is about 90% efficient compared to about 40% efficiency using direct natural gas cooking (LBL, 1993). Cooking and clothes drying, the largest loads of ‘other loads’, would also be in the same time frame as water heating (waking hours) and in the absence of time data, the sector is assumed to be constant during these hours. Other minor uses include swimming pool heaters, outdoor grills, and outdoor lighting (natural gas). Swimming pool heaters can be replaced by efficient heat pumps, and gas lighting by much more efficient LED lamps; because this electrified load is small, uncertainties in our assumptions will have little overall effect. The method used to obtain the electrified loads shown in Table 4 was complex and will be discussed fully in a full paper in preparation. The result is an annual electrified residential load of 668 TWh(e). This does not include loads already included in the 2006 EIA electricity load sector.

Tab. 4: Residential monthly calculated loads for 2006.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	Million cu. ft of Gas	**COP**	**Cu. ft Nat Gas Non-SH WH Equiv.**	**Month**	**Natural Gas WH model**	**Natural Gas SH Model**	**Total thermal energy provided (TWh) SH**	**Total Thermal Energy provided (TWh) WH**	**Total electrical Power Needed (TWh) SH**	**Total electrical Power Needed (TWh) WH**	**Cooking TWh electrical needed**	**Clothes Dryers TWh electrical needed**	**Other TWh electrical needed**	**Total other TWh electrical needed**	**Total Residential TWh electrical needed**
1	713,698	2	26,161	687,537	95,524	592,013	220.1	20.9	110	10.5	2.7	3.1	2.1	7.9	128.4
2	702,280	2	26,161	676,119	95,524	580,595	215.8	20.9	107.9	10.5	2.7	3.1	2.1	7.9	126.2
3	625,925	3	26,161	599,764	92,212	507,552	188.7	20.2	62.9	6.7	2.7	3.1	2.1	7.9	77.5
4	355,496	3	26,161	329,335	88,901	240,434	89.4	19.5	29.8	6.5	2.7	3.1	2.1	7.9	44.2
5	203,512	4	26,161	177,351	85,590	91,762	34.1	18.7	8.5	4.7	2.7	3.1	2.1	7.9	21.1
6	141,157	4	26,161	114,996	82,278	32,718	12.2	18.0	3.0	4.5	2.7	3.1	2.1	7.9	15.4
7	115,586	4	26,161	89,425	82,278	7,147	2.7	18.0	0.7	4.5	2.7	3.1	2.1	7.9	13.0
8	108,439	4	26,161	82,278	82,278	0	0.0	18.0	0.0	4.5	2.7	3.1	2.1	7.9	12.4
9	124,922	3	26,161	98,761	85,590	13,172	4.9	18.7	1.6	6.2	2.7	3.1	2.1	7.9	15.7
10	240,448	3	26,161	214,287	88,901	125,386	46.6	19.5	15.5	6.5	2.7	3.1	2.1	7.9	29.9
11	413,409	2	26,161	387,248	92,212	295,036	109.7	20.2	54.8	10.1	2.7	3.1	2.1	7.9	72.8
12	623,595	2	26,161	597,434	95,524	501,910	186.6	20.9	93.3	10.5	2.7	3.1	2.1	7.9	111.6
Total 2006	4,368,467		313,930		1,066,81	2,987,72	1110.6	233.6	488.2	85.6	32.0	37.1	25.4	94.5	668.2

9.2 Commercial Electrification

Table 5 shows estimates of TWh of non-electricity commercial thermal load for various fuels used in the commercial sector, plus an estimate of best current usage efficiency of usage. Non-water heating and non-space heating loads include miscellaneous uses, such as cooking, pumps, emergency generators, and combined heat and power in commercial buildings.

Tab. 5: Annual calculated TWh(th) required for the electrified commercial sector.

	2006 Quads	**Fossil Fuel Efficiency**	**Assumed COP**
Natural Gas			
Space Heating	1.26	0.8	Variable
Space Cooling	0.02	0.8	2
Water Heating	0.55	0.62	Variable
Cooking	0.23	0.4	0.9
Other Uses	0.94	0.5	1
Delivered Energy	3.01		
Distillate Fuel Oil			
Space Heating	0.18	0.8	Variable
Water Heating	0.07	0.62	Variable
Other Uses	0.22	0.5	1
Delivered Energy	0.46		
Marketed Biomass	0.12	0.8	
Other	0.38	0.8	
Total Quads	7.44		
Total TWh(th)	2180		

Table 6 shows a electrical load derivation for the commercial sector similar to Table 4 for the Residential sector. Diurnally all commercial sectors are taken to be is taken to be at half maximum value between 6AM and 9AM, full value between 9AM and 6PM, half value between 6 PM and 9PM and zero otherwise. The final annual figure arrived at was 442 TWh(e) and the monthly distribution is given in Column 17 of Fig. 6. Like residential heating, this shows a strong winter bias.

Tab. 6. Calculated monthly commercial loads for 2006.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Month	2006 Monthly Use MCF	Assumed COP	WH Usage MCF	SH Usage MCF	Non SH WH Usage MCF	Cooking MCF Use	Space Cooling MCF Use	Other Use MCF	CSH (TWh) Thermal Delivered	CWH (TWh) Thermal Delivered	CSH (TWh) Electrical Needed	CWH (TWh) Electrical Needed	Cooking (TWh) Electrical Needed	Space Cooling (TWh) Electrical Needed	Other (TWh) Electrical Needed	Total (TWh) Electrical Needed
1	396,993	2	46,480	234750	115763	18058	0	97706	90.1	10.0	45.1	5.0	2.5	0.0	18.7	71.3
2	390,067	2	46,480	230223	113365	18058	0	95307	88.4	10.0	44.2	5.0	2.5	0.0	18.2	69.9
3	352,874	3	44,868	201259	106747	18058	0	88689	77.3	9.7	25.8	3.2	2.5	0.0	17.0	48.4
4	225,687	3	43,257	95339	87091	18058	1422	67612	36.6	9.3	12.2	3.1	2.5	0.1	12.9	30.8
5	160,316	4	41,646	36386	82284	18058	2843	61383	14.0	9.0	3.5	2.2	2.5	0.1	11.7	20.1
6	134,267	4	40,035	12974	81259	18058	4265	58937	5.0	8.6	1.2	2.2	2.5	0.2	11.3	17.4
7	121,913	4	40,035	2834	79045	18058	5686	55301	1.1	8.6	0.3	2.2	2.5	0.3	10.6	15.8
8	126,396	4	40,035	0	86362	18058	4265	64039	0.0	8.6	0.0	2.2	2.5	0.2	12.3	17.1
9	133,020	3	41,646	5223	86151	18058	2843	65251	2.0	9.0	0.7	3.0	2.5	0.1	12.5	18.8
10	187,618	3	43,257	49719	94642	18058	1422	75163	19.1	9.3	6.4	3.1	2.5	0.1	14.4	26.4
11	256,210	2	44,868	116990	94352	18058	0	76294	44.9	9.7	22.5	4.8	2.5	0.0	14.6	44.4
12	346,668	2	46,480	199022	101167	18058	0	83109	76.4	10.0	38.2	5.0	2.5	0.0	15.9	61.6
	2,832,029		519,084	1184719	1128226	216,692	22745	888789	454.7	112.1	199.9	41.1	30.0	2.8	170.0	442.0

9.3 Industrial Sector Electrification

Electricity is already used to supply process heat for industry; electric arc furnaces are one example. It should be cheaper to supply high temperature solar heat at a peak of 60-70% efficiency at the point of use than to run a turbogenerator to produce solar electricity at 10-40% efficiency and then turn the electricity into high temperature heat, but for the purposes of this study, we have assumed that thermal energy is supplied as grid electricity which is used as efficiently as possible. In 2006, 10.24 Quads of energy was supplied to industry as shown in Table 7. Electrical and renewable supplies to industry are assumed already included in the previous electrical grid load figure. It is assumed that 30% of industrial heat is below 100°C (Werner, 2007) and can be replaced by heat pumps using electricity at a COP of 3.

Tab. 7. Industrial Sector Energy

	Quads Thermal	Efficiency before Electrification	Efficiency or COP after Electrification	Net Quads Electric	TWh electric needed
LPG	0.12	0.20	0.90	0.03	7.8
Motor Gasoline	0.32	0.20	0.90	0.07	20.8
Distillate Fuel Oil	1.30	0.25	0.90	0.36	105.8
Distillate Self Generation	0.06	0.40	1.00	0.02	9.8
Residual Fuel Oil/Petroleum Coke	0.55	0.83	1.00	0.46	133.8
Natural Gas Boiler fuel	2.14	0.83	0.90	1.97	578.4
Natural Gas Self Generation	0.72	0.40	1.00	0.29	133.6
Natural Gas Direct Heat*	2.44	0.70	1.60	1.07	312.9
Metallurgical Coal, Coke**	0.72	Biomass fueled virgin iron stage presumed	Electric arc furnace	0.21	61.4
Coal for Boilers*	0.77	0.83	0.90	0.71	207.2
Coal Self Generation	1.22	0.30	1.00	0.37	162.3
Total Industrial	10.24			5.55	1726.0
* 30% of process heat demand is <100°C and uses Heat Pumps thus 2/3 of heat at 0.9 efficiency and 1/3 at COP 3					

Metallurgical coal contains carbon that reduces iron ore into virgin iron as well as being combusted to keep the process at high temperature. It is assumed that can be supplied from biomass charcoal, and, indeed, wood was used in former times for this purpose. Development of a hydrogen gas iron ore reduction process might allow solar and wind to replace charcoal and provide the fuel for iron-making with much less land impact (Carmo de Lima et al, 2004; ITP, 2007) but this is not yet established technology. Zero carbon methods using electrolysis are also being investigated as part of a EU program called ULCOS. (ULCOS, 2011).

Table 7 shows our accumulated data from the foregoing discussion of the industrial sector, which results in a total of 1726 TWh(e), excluding metallurgical fuel. Natural gas usage in the industrial sector (Table 8) is used to suggest a model of monthly usage variations. These are modest with a mild bias toward increased winter usage. Diurnally, the industrial energy used in this model is assumed to be constant over 24 hours.

9.4 Transport Sector Electrification

a) Surface transport

Electric cars are beginning to enter the market in commercial quantities and electric trucks, buses and vans are in development or operation. Information on such vehicles has been announced by some manufacturers or web sites. The 2010 5-seater 1.521 tonne (Nissan Leaf, 2011) Nissan Leaf EV is stated to offer a range of 175 km on the new European Driving Cycle on a 24 kWh Li-ion battery or 0.22 kWh/mile. The 2012 5-7 seat 1.739 tonne Tesla S sedan with a Li-ion battery realises a 483 km range (Tesla S, 2011) with a 85 kWh battery (Tesla S battery, 2011), for 0.26 kWh/mile. The latter has a range and passenger capacity similar to many US fossil-fuelled cars, and a luggage capacity similar to SUVs, so a 0.25 kWh/mile figure between the Leak and the Tesla is adopted as reflecting a likely standard vehicle performance.

Tab. 8: Calculation of the load for the electrified transport sector. As a first guess, we can assume that all electrified vehicle sectors will have electricity consumption in proportion to their current petroleum usage. Cars, trucks and buses constitute about 93% of current energy consumption and should be more or less consistent in this regard.

Vehicle Type	Quads (th)	Relative Energy Use	Annual TWh(e)
Cars/Light Trucks	16.55	0.688	663
Commercial Light Trucks	0.6	0.025	24
Bus Transportation	0.26	0.011	10
Freight Trucks	4.9	0.204	196
Rail, Passenger	0.04	0.002	2
Rail, Freight	0.56	0.023	22
Shipping, Domestic	0.25	0.010	10
Shipping, International	0.7	0.029	28
Recreational Boats	0.18	0.007	7
Total	24.04	1.000	**962**

The U.S. national vehicle fleet-miles travelled by cars and light trucks were 2.65 x 10^{12} in 2006 (EIA, 2007). Categories of non-aircraft transport usage obtained from the EIA (2007) are shown in Table 8. Using the usage in other sectors is held in the same ratio to personal vehicles, the electricity used in the transport sector at this consumption would be 962 TWh(e) per year. Vehicle transport in the United States is very uniform in total miles travelled per month, varying from roughly 5% below average in winter to 5% above average in summer(EIA, 2011). For the purposes of this study we assume a simple linear variation by month between these extremes, with the lowest on February 1st and the highest on August 1. A simple assumption of charging at twice the rate at night between 6PM and 6AM as in the hours between 6AM and 6PM is made, but the reality may be better. Battery capacity as large as an electric car fleet should be able to provide additional flexibility in the system for better grid load allocation. Fluctuations in load could be offset by charging parts of the national car fleet at particular times, using price signals, but this is not assumed.

b) Air transport

While small electric aircraft have begun to be developed, long range heavier-than-air passenger aircraft seem unlikely (although not impossible to rule out). These are, therefore, not included in the transport electricity load. High speed trains have the potential to largely eliminate short-distance air travel, but according to the IPCC (1999), flight stages of 800 km or less are estimated to represent only about 15-20% of all scheduled passenger operations (expressed in terms of available seat-km). For long-distance high speed travel over land, partial vacuum or pneumatic tube trains are possible, but have not yet been developed. For transoceanic travel, the continued usage of aircraft seems necessary. Fast blimp or dirigible approaches might be more energy efficient for freight, but would downgrade passenger ocean-crossing times to those of the 1930's.

The best near-term option is the substitution of a low emissions biofuel for petroleum-based aircraft fuel. Biomass-fuelled jet aircraft have already flown (Schwarz, 2009). The aviation energy sector is much smaller than for land vehicles at 2.91 Quads in 2006, about 10.3% of all US transport energy. We calculate that to power US aircraft alone would require the increase in 2009 global ethanol (or equivalent) production by almost 250%. It is feasible, but easier if competition from biomass land transport is absent. *A redirection of the biomass market away from land vehicle supply, which is clearly beyond reach globally, to aircraft supply is completely consistent with the vehicular move toward grid electricity advocated in this paper.* In the longer term, there would seem to be a strong land-use case for development of solar/wind hydrogen-fueled aircraft before mid-century; there is little doubt that such aircraft could be developed. The sooner this is done, the less impact the biomass energy sector will have on food production.

9.5 Total Electrified Market

The derived sectoral load data was accumulated and adapted to the UTC time zone. Table 9 shows the annual derived electricity load by sector. The annual figures are separated into monthly figures using the previously described methods. The total load is 7115 TWh(e), 73% higher than the electricity-only load derived earlier from FERC data. Fig. 3 shows the annual output pattern, which now has a strong winter peak due to seasonal heating loads.

Tab. 9: The total electrified load excluding metallurgical steel and aircraft usage.

Sector	Twh(e)	Percent
Stationary Electricity	3317	46.6%
Residential	668	9.4%
Commercial	442	6.2%
Industrial	1726	24.3%
Transport	962	13.5%
Total	7115	100.0%

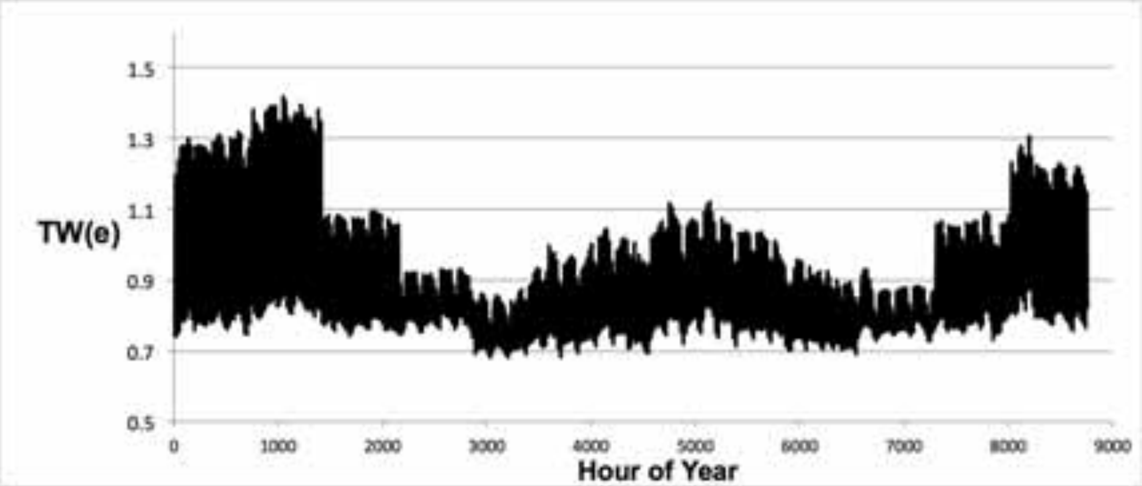


Fig. 3: Full electric load synthesized for 2006. The derived system load peak is 1419GW(e), almost double the actual 2006 electrical peak load, and the annual load minimum is 675 GW(e). The step functions are artifacts of the monthly seasonal change assumptions, but smoothing the data did not improve the load matches later calculated.

10. Results of Total Load Matching

Using the data for electrified transport and heating sectors provided in the previous section, the load match was calculated using the methods described in the companion paper and an enlarged national array of wind generators and CST storage plants. Table 10 shows the calculated load match results for 25% and 35% redundancy cases. Comparing these with the results for the electricity-only system in the companion paper, the electricity-only system peak load rose from 774 GW to 1419 GW, a rise of 83%, but the peak system requirement rose only from 1282 GW of Solar and 1100 GW of wind to 2610 and 1596 GW of wind, an overall rise of 77%. This suggests that the solar/wind system is better matched to the total energy supply than the electricity supply.

The 35% case with 67.7% solar and 67.3% wind shows the best match of 100% for a given storage capacity with 16 hours of storage in the solar fleet. However, if up to 2% of backup fuel is allowed to complete the load match, the case of 25% redundancy and 4 hours of storage is likely to be close to the economic choice, with 8% less generation capital cost and 6 fewer hours of solar storage. Even two hours of storage makes a big improvement in coverage over the zero storage case.

Table 10: Percentage of 2006 total electrified load coverage from combined wind and solar of 25% and 35% redundancy according to relative fraction of wind and solar potential, and hours of solar thermal storage.

25 % redundancy			Hours of Storage										
	Solar Installed (GW)	Wind Installed (GW)	0	2	4	6	8	10	12	14	16	18	20
Solar = 57.7%, Wind = 67.3%	2609.68	1596.00	82.79%	97.05%	98.95%	99.37%	99.48%	99.55%	99.62%	99.69%	99.76%	99.83%	99.90%
Solar = 62.5%, Wind = 62.5%	2826.78	1482.17	80.39%	97.01%	99.01%	99.31%	99.39%	99.46%	99.54%	99.61%	99.69%	99.77%	99.84%
Solar = 78.8%, Wind = 46.3%	3564.00	1097.99	70.47%	96.23%	98.09%	98.43%	98.52%	98.62%	98.71%	98.81%	98.90%	99.00%	99.09%
Solar = 95.%, Wind = 30.%	4296.70	711.44	59.47%	93.88%	95.92%	96.37%	96.71%	96.94%	97.17%	97.40%	97.60%	97.72%	97.83%

Load Coverage	<70%	>70%	>80%	>95%	>98%	>99%	100%

35 % redundancy			Hours of Storage										
	Solar Installed (GW)	Wind Installed (GW)	0	2	4	6	8	10	12	14	16	18	20
Solar = 67.7%, Wind = 67.3%	3062	1596	82.79%	98.26%	99.45%	99.59%	99.67%	99.76%	99.84%	99.92%	100.00%	100.00%	100.00%
Solar = 83.8%, Wind = 51.2%	3790	1214	73.57%	97.93%	99.04%	99.14%	99.24%	99.35%	99.45%	99.55%	99.65%	99.76%	99.86%
Solar = 100.%, Wind = 35.%	4523	830	62.51%	96.55%	97.86%	98.08%	98.21%	98.33%	98.45%	98.57%	98.69%	98.82%	98.94%

11. Discussion

This paper has explored how the USA could have been entirely powered by wind and solar alone in 2006 had we used current wind and solar storage technology together with the appropriate demand-side electric vehicles, heat pumps and other end use technology. This could be done using entirely local energy resources, without oil and gas imports, and without significant operational carbon pollution. Several

The wind generators modelled are very similar to those being built today and have no storage. However, the optimized solar plant layouts were - to our surprise - unlike today's field layouts because they take the role of peaking plants inside an integrated continental system that includes a large but inflexible wind input. The same components would be used as now, but the plants would have relatively large steam turbines for their field size, and would be operated at a lower CF than current plants. Storage would be 10 hours to achieve 100% coverage with 35% plant redundancy. If up to 2% fuel backup is allowed, this would drop to 4-6 hours and 25% redundancy, a 7.5% reduction in wind and solar plant installation cost. Three hours of storage may be possible if combustable backup is enlarged slightly.

The wind/solar system is over-designed by 25-35% of available annual generation to ensure load coverage when solar and wind are both scarce. However, this the extra electricity output can be utilized by production of hydrogen. One application is to use the dumped electricity to produce the combustable hydrogen backup fuel but this otherwise neat solution requires very expensive containment vessels. However, there is another, more comprehensive possibility. If produced from otherwise dumped electricity at 78% dissociation efficiency, in 2006 the USA would have needed 2.91 Quads of thermal energy = 853/0.78 TWh(e) = 1094 TWh(e) for aircraft propulsion and 0.51 Quads = 149.5 TW(th)/0.78 = 192 TWh(e) of hydrogen for iron ore reduction. This represents an additional 1286 TWh(e), an apparent increase of 18% in the total electricity generation requirement. In addition, to supply a 2% load deficit at a round-trip efficiency of 29% would require a 7% increase in TWh(e) used. The total, 25%, is within the 25% to 35% of the electricity that would otherwise have been dumped. This has several advantages; (1) fuel and process heat production is shifted away from biomass and its land use issues; (2) the solar or wind plants have an increased income selling excess (off-peak?) electricity to industries who need the hydrogen fuel and could generate what they need on their premises (4) no significant new generation infrastructure is needed and (5) there would be a possibility of "re-buying" the hydrogen from the industries via pipelines instead of natural gas, especially if major industries could be near the solar plants. This scenario is not an approach for today, but illustrates how research into hydrogen aircraft and hydrogen ore reduction could result in a highly efficient and emissions free energy sector where little solar and wind energy would be wasted.

This paper did not address one important technical possibility, that low cost electrical storage might become available for wind and solar. The advent of any low cost electrical storage would probably significantly change the mix of technologies used, for PV and wind could compete with CST for the dispatchable electricity market. Because any such battery storage would be short-term, the load-matching advantages of seasonal and diurnal mixing of solar and wind outputs would remain, although a widely distributed PV network not solely in the South-West USA might end up with a different load match fraction. The need need to exploit limited wind resources preferentially would remain as a means of allaying the high winter energy loads, and dropping cost. As with the CST systems modelled, there would be no baseload or peaking in the system, merely a multitude of individual load-following plants each plant buying and selling to the the grid in a spot market regulate load coverage. It could be difficult to justify the complexity of CST if such PV/ Wind/battery technology were to arise. In the meantime, however, CST/ Wind offers a unique technical solution - low emissions and a sufficiently large global resource base - that otherwise does not exist.

The authors believe that CST/Wind as a viable zero or near zero emissions strategy deserves much more confirmation and elaboration. It would use the largest and most fully sustainable resources. It is a plausible and mostly proven technical pathway. It would eliminate imported fuel for large emitters like the USA, India and China which have large desert areas, regions of high winds, and large populations.

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