Transition to 100% Renewable Energy in California and the USA in 12 years

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Summary

Converting all fossil fuel electric energy production to solar+wind+battery storage, most land vehicles to electric, and most natural gas use to electric for the state of California will cost each resident of California roughly **$3.75** per day for the next **12** years, assuming a 12 year roll out. At the end of this, the value returned will be potentially **$8.67** per day per resident, for a total of **$4,738** per year in savings returned per resident – over **$18,953** every year for the average household of 4 (2019 dollars). The total cost would be **$650.2 billion**, and occupy **316.6** square miles – **0.193%** of the area of the state (see Fig 10). It will save **227 Million metric tons** of green house gasses in the form of CO_2. This summary assumes a 98% solar balance wind power ratio for the state. After completion, this generation system would provide power at almost zero operations and maintenance cost – less than $0.01/kwh – indefinitely, using the power of the sun. Over the last two years California increased solar generation by **8,144** Gwh, **9.05%** of the rate needed to achieve these goals. The choices made on who owns this generation will determine who will get the savings from this very low cost system.

Extrapolating these results to the entire United States of America:

Cost per resident of the USA roughly **$6.42** per day for the next 12 years, assuming a 12 year roll out. At the end of this, the value returned will be potentially **$8.67** per day per resident, for a total of **$5,105** per year in savings returned per resident – over **$20,419** every year for the average household of 4 (2019 dollars). The total cost would be **$9.20 trillion**, and occupy **3,313** square miles – **0.087%** of the area of the country. It will save **6,870 Million metric tons** of green house gasses in the form of CO_2. This summary assumes a 50% solar balance wind power ratio for the country.

Current State of California

2018 Total System Electric Generation in Gigawatt Hours

Fuel Type	California In-State Generation (GWh)	Percent of California In-State Generation	Northwest Imports (GWh)	Southwest Imports (GWh)	California Energy Mix (GWh)	California Power Mix
Coal	294	0.15%	399	8,740	9,433	3.30%
Large Hydro	22,096	11.34%	7,418	985	30,499	10.68%
Natural Gas	90,691	46.54%	49	8,904	99,644	34.91%
Nuclear	18,268	9.38%	0	7,573	25,841	9.05%
Oil	35	0.02%	0	0	35	0.01%
Other (Petroleum Coke/Waste Heat)	430	0.22%	0	9	439	0.15%
Renewables	63,028	32.35%	14,074	12,400	89,502	31.36%
Biomass	*5,909*	*3.03%*	*772*	*26*	*6,707*	*2.35%*
Geothermal	*11,528*	*5.92%*	*171*	*1,269*	*12,968*	*4.54%*
Small Hydro	*4,248*	*2.18%*	*334*	*1*	*4,583*	*1.61%*
Solar	*27,265*	*13.99%*	*174*	*5,094*	*32,533*	*11.40%*
Wind	*14,078*	*7.23%*	*12,623*	*6,010*	*32,711*	*11.46%*
Unspecified Sources of Power	N/A	N/A	17,576	12,519	30,095	10.54%
Total	194,842	100.00%	39,517	51,130	285,488	100.00%

Fig 1. Source California Energy Commission

Of the **226,043** Gwh currently used in California (loads not generation), renewables are currently generating **89,502** Gwh from in state and out of state renewable resources. This model uses the difference of those as the basis for the electric generation portion to replace current fossil fuel use, both in and out of state.

Solar and wind power currently are roughly equal contributors to the renewable mix, supplying a total of **22.9%** of the total generation. They complement each other in that wind power tends to be higher during periods when there is little or no solar power. Also it tends to be higher in the winter when solar power is lower. Unfortunately, the best places for wind power in California have been hampered by local regulations on height or placement or BLM restrictions such that the potential for additional resources within California is very limited to currently on the order of several Gw. For the purposes of this study the wind component has been reduced to 3 Gw for in-state additional generation.

This leaves the bulk of the generation to solar with energy storage (in this study entirely battery based). Our studies have shown that a battery storage system which stores **4** hours times the peak solar power generation value of a solar system provides enough power to operate all loads of a system from one day to the next, even in winter, provided the solar power (or grid power) recharges the battery each day. In our simulation model, we used solar power from across the state, using 3 regions to draw solar power from – Northern California using Oakland solar statistics, Los Angeles, and San Diego. We assume the grid can distribute power from one region to other. See Appendix B for detail on PV/storage ratios.

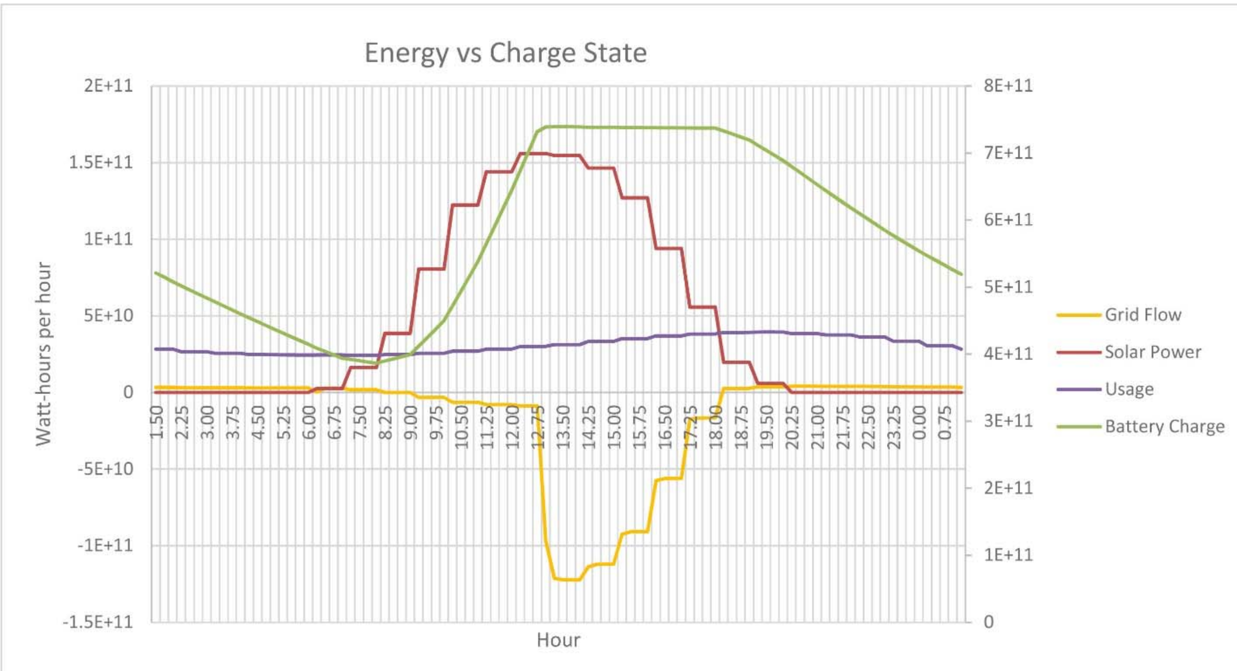

Fig 2A. Summer – Generation, usage, grid flow, and energy storage charge state – electric generation replacement only

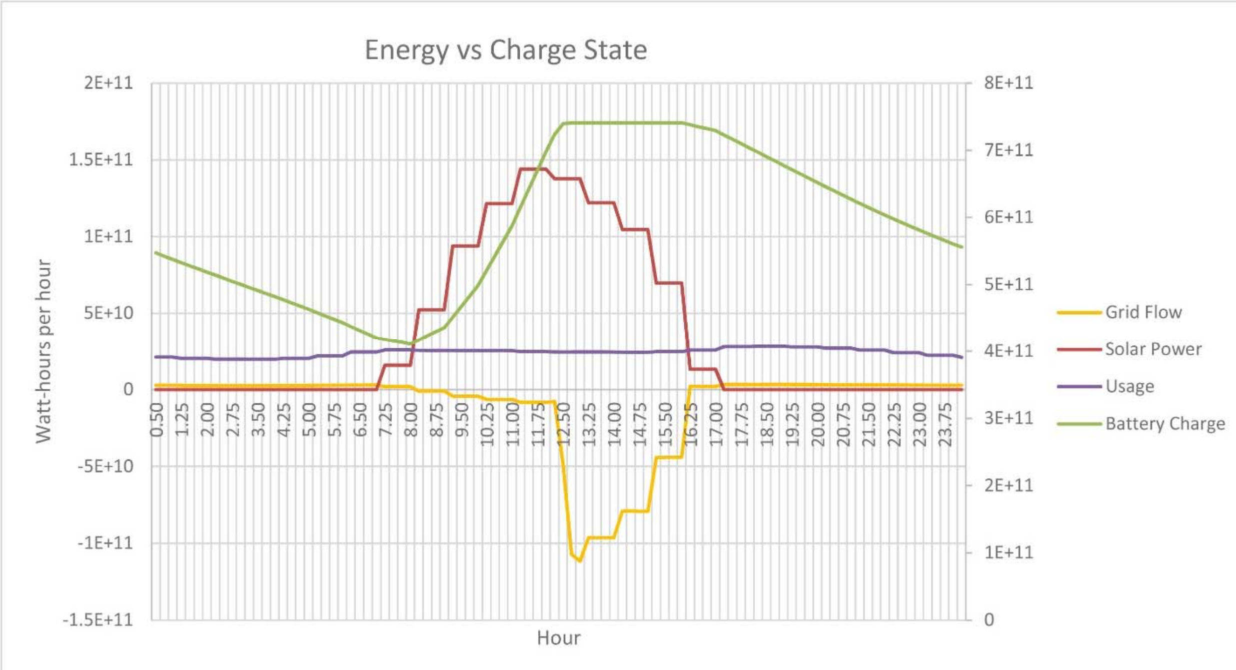

Fig 2B. Winter – Generation, usage, grid flow, and energy storage charge state – electric generation replacement only

Fig 2A & B shows typical summer and winter days, with the battery storage (green) filling in the am from solar power (red), with the difference running the system loads (blue). The excess power (yellow) can be exported and sold.

There is more than enough roof space, parking lot area, and nearby land area to generate the required solar power for California load use, for all the components modeled in this study. By using such a distributed energy model, additional transmission cost build out is vastly reduced or eliminated. The grid becomes vastly more resilient also because all regions of the state will have local generation and storage resources that can power that area in the event of partial grid failure due to downed power lines or infrastructure damage.

Google Project Sunroof estimates 113Gw and 198,000 GWh of energy could be produced from all usable rooftop space in California.

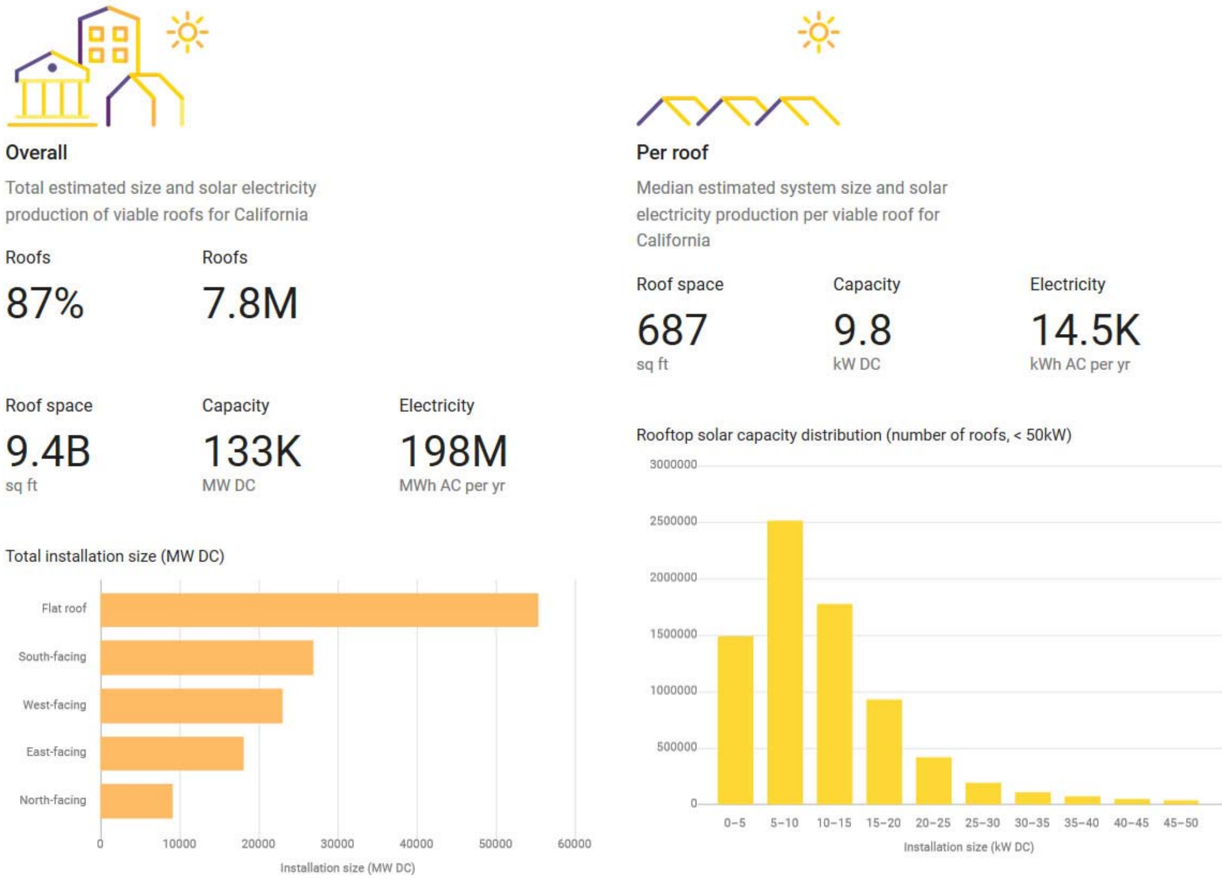

Fig 3. Project Sunroof estimates of available solar energy generation from California rooftops.

ELECTRIC GENERATION

The California Energy Commission load data shows load use in 2018 as 226,043 Gwh. We've subtracted the 89,502 Gwh of existing renewables, which leaves 136,541 Gwh needed using solar power, and using a 1800 kwh/kw per year capacity factor (AC) will require **74.3** Gw of solar power. This is close to the total 133 Gw Google estimates is available, but it's unlikely that all will be used. Parking areas and ground mounts adjacent to properties can also be prime sources for solar generation. We've used a mix of 20% residential, 60% commercial, and 20% large scale installations for the initial first stage generation, then eventually a shift to 10%, 10%, 80% (residential, commercial, industrial scale in that order). This model places the bulk of the ownership of the solar in the hands of residential and commercial customers in the beginning, and power would be sold back to the utilities and CCAs.

A number of projections have considered the cost of solar power generation over the next 30 years. Silicon PV modules with warrantied lifetimes of 30 years, and likely useful lifetimes in excess of 50 years are currently selling at \$0.40-\$0.60/watt. NREL (reference Science April 2017) estimates cost to get to as low as \$0.25/watt. System level costs will decrease also, but not likely as much as PV costs. Labor installation costs will most likely increase, rather than decrease.

We've used the current cost rates from Fig 4, with a 50% over generation cost (more on than later) for the total cost of **$240.1** Billion. Using 98% solar, balance wind, the additional wind systems cost is $1.95 B at $1.70 /watt.

The total battery storage capacity needed is 300.8 Gwh. We've used an average cost over the ramp period of $110 / kwh for the storage. The total storage cost is $33.09 B.

Note the storage cost only represents 12.0% of the total system costs.

This puts the total electric generation cost with storage at $275.14B.

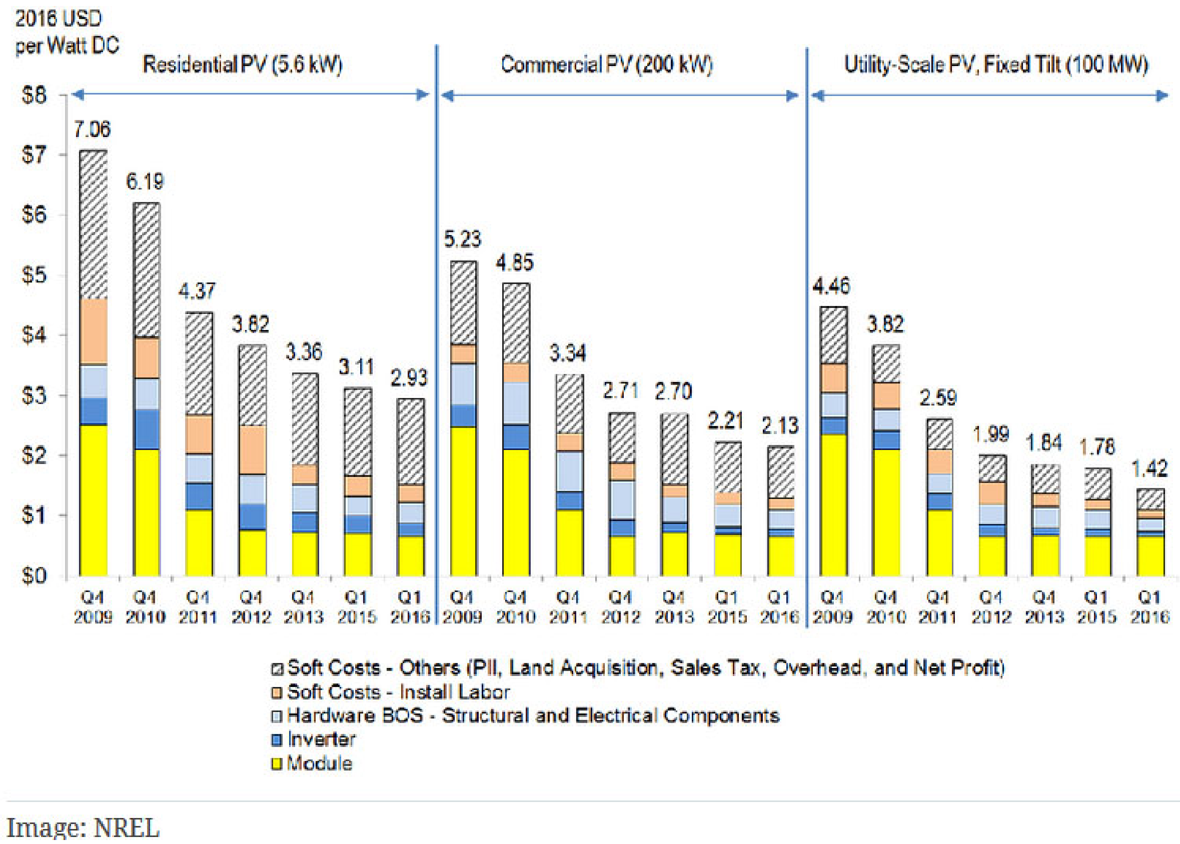

Fig 4 – Cost of PV

ELECTRIC VEHICLES

Total vehicle driven miles in California in 2016 was 195.2 billion. The mean miles driven per household was 31.7 miles per day, consuming 1.3 gallons of fuel. We've used 7.5 kwh/gal as an equivalent value for all EVs – a simplification but reasonable based on energy used in light vehicles. Heavier vehicles will consume more but in general the energy used will scale with weight. This results in a total of 116,837 GWh per year needed to power these vehicles. This displaces 15.58 billion gallons of gas use per year.

The additional solar+wind+storage needed to offset this use costs $193.36B.

Over the ramp period, most vehicles will need to be replaced – the anticipation here is that they all be replaced with EVs. Current models already have similar range as existing gas vehicles. Long haul trucks may still need hybrid power, preferably powered by biofuels.

These electric vehicles will also have a huge energy storage capacity. Using an estimated average range of 300mi per vehicle, the total capacity of all these vehicles is 2237 Gwh –2.8 times the total energy storage needed for the generation system.

The cost savings per day per person in California, vs the $4.00/gal current gas prices, is $4.32. Note this savings alone is 1.2 times the cost for ALL the generation costs for going all renewable.

NATURAL GAS

California currently imports 90% of their natural gas use, which powers electric generation, home & business heating, cooking, drying and other appliances. In homes, fully 45% of gas use is for water heating. This can easily (and at low cost) be replaced by electric water heaters. Dryers are also replaceable with electric versions at low cost. Cooking and heating require larger cost outlays, but combinations of inductive cooking, microwave heating/cooking, and heat pumps for home heating and air conditioning could replace ALL natural gas use with electric power.

Natural gas use for 2016 excluding electric generation was 1188.44 billion cubic foot. We've used the bcf to kwh conversion factor used by the electric generation to convert this to 113,813 Gwh of power needed.

The solar plus storage adds an additional $181.72B to the total costs.

TOTALS

The total cost of the 3 components above is **$650.2B**. A simple averaging of this cost over the ramp period is **$54.2B** per year. Cost then for the roughly 39,250,000 population of California yields **$1,370** per year, or $3.75 per day.

SEASONAL COMPENSATION

Although the above calculations for solar provide the total energy needed, average daily solar generation is less in winter than in summer. Clouding also affects regional areas. Fig 5 shows the first stage state solar production with solar production equal to loads annually with solar (red), the loads (blue), and the net power export (yellow).

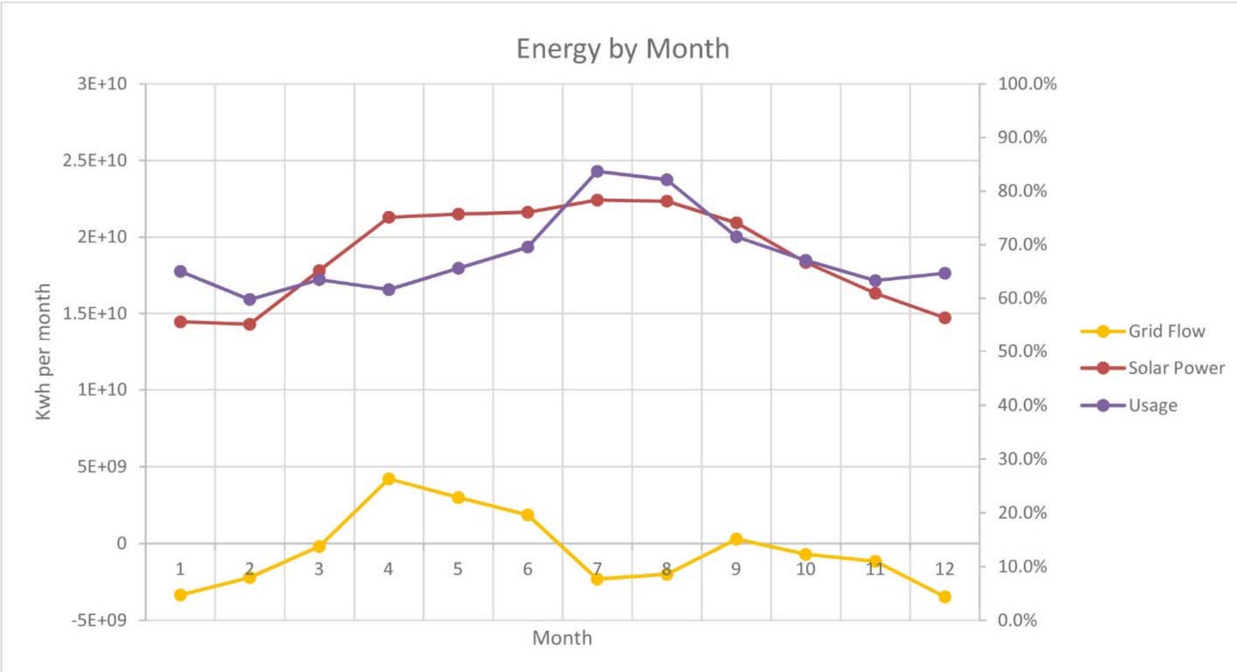

Fig. 5.

WINTER NATURAL GAS USE

Figure 6 show monthly natural gas use, excluding energy used for electric generation. Gas use nearly doubles in winter.

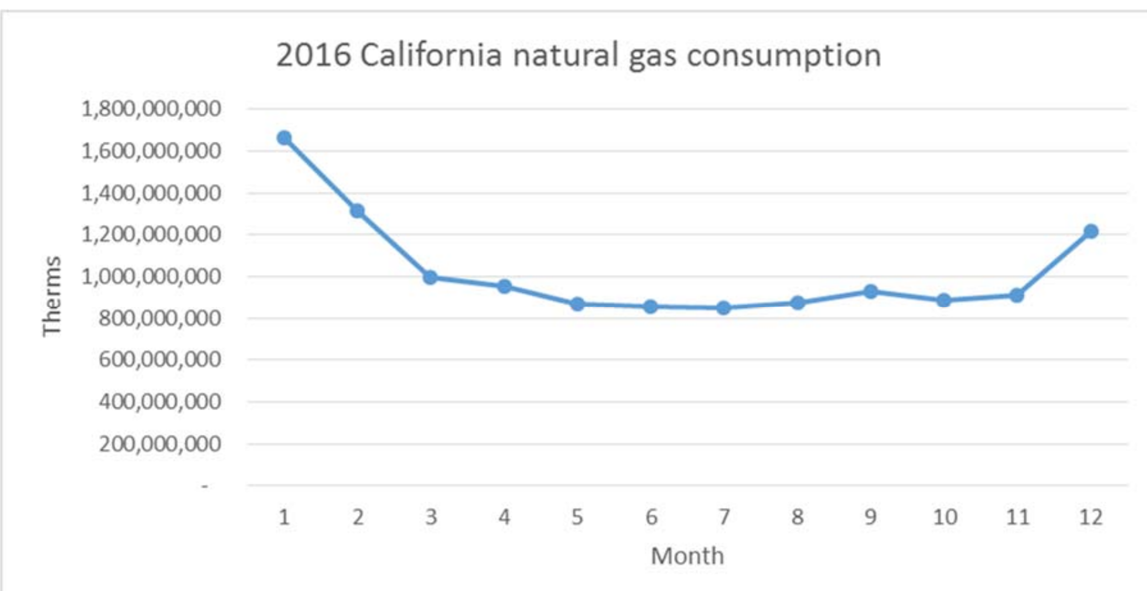

Fig 6.

Solution – Over Generation

The simplest solution for this is to increase the overall solar generation capacity, so that even in winter there is sufficient capacity to meet loads. The excess summer capacity could be exported out of state, or used to create renewable fuels such as hydrogen. Using hourly use data from the CEC the following figure shows power usage for the state, with solar power weighted from 3 sources – Northern California using Oakland solar statistics, Los Angeles, and San Diego and adding 50% over generation. This curve also includes seasonal variation of electric generation and natural gas use. Fig 7 shows the current electric generation use replaced by over generated renewables, adding a total of 111.5 Gw of solar power to the current existing renewables. Green house gas savings are shown for both the battery alone (dotted green) and the combined solar+battery (dotted blue).

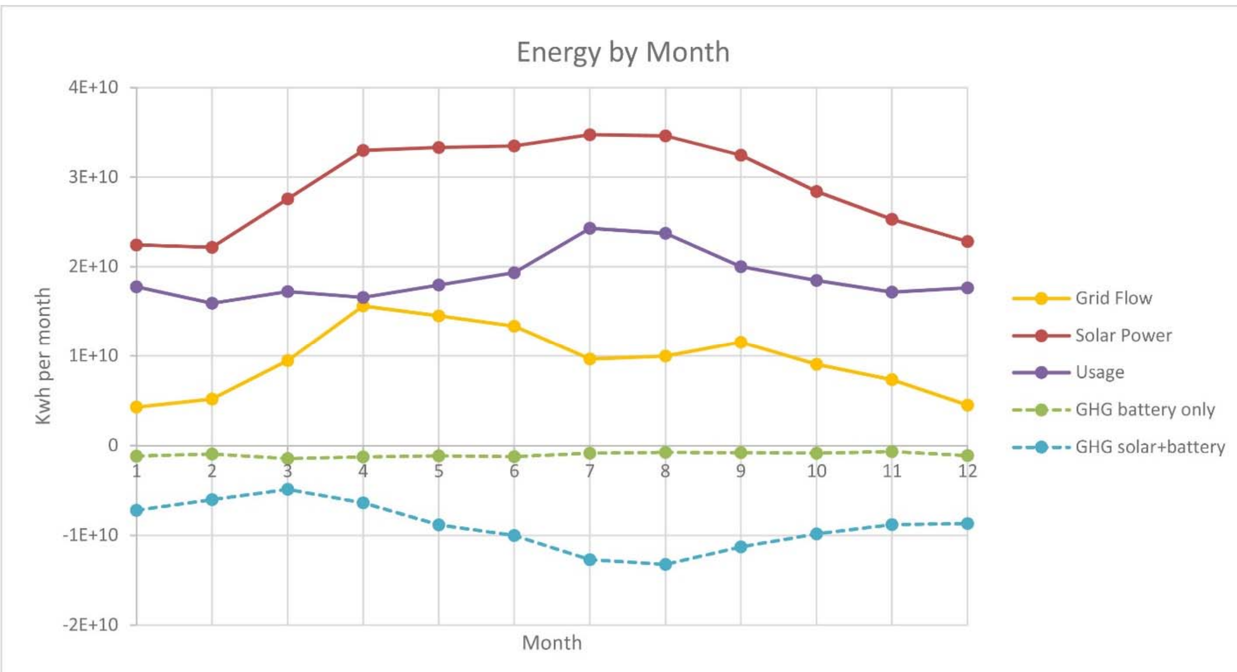

Fig 7 – Solar generation compensated for seasonal variation, with state monthly use data – CPS model with CEC usage data 2018 – 100% renewables – GHG savings for storage only in green, solar+storage savings in blue units in kg

The storage needed is always only the capacity needed to get from one day to the next. It will always be filled the next morning from solar generation or the grid (when cloudy, energy will come from other parts of the grid with less cloud cover). Also it is expected that this net export would result in a substantial net income for the state. As other states adopt this model, the potential for selling the power out of state may be reduced.

We also expect over the ramp timeframe of this study that costs will decrease by 30-40%. These reductions have not been included in this model.

The value of the excess generation, for example sold at 179,923/kwh, for the 179,923 Gwh of excess power, could generate $17.99 B in revenue annually.

Worse Case Scenarios

Although the above calculations for solar provide the total energy needed and cover seasonal variations, it's important to imagine & compensate for worse case scenarios. What if there is a string of cloudy days? With wildfires, what if there are strings of smoke obscured days?

There are several options, one option is vehicle to grid storage. The 30+ million EVs with an average of 300 mile range will have a total capacity of 2237 Gwh - more than 2.8 times the stationary storage capacity for the one day requirement. An obvious solution is then to buy back stored energy from EVs during extended cloudy day events. If all vehicles participated, there would be more than enough capacity for even the most severe extended cloudy day event.

Hydrogen production using fuel cells or a combination of electrolysis (for production) and fuel cells (for generation) is also possible. The disadvantage is that 3-4X the energy is needed to create the fuel, store it, and then regenerate power when needed.

Biofuels operating existing electric generation systems may be the preferred solution, or a combination of the above.

Wind power also tends to complement solar generation, and tends to be higher in the winter than in the summer. The cloud events that accompany multiple low power solar generation days would also generate higher than normal winds, which is a potential alternative to the above options. Besides in-state generation purchasing from out of state is an option, but incurs transmission costs.

Benefits

With the current cost of electric energy in California at average $0.23 /kwh, solar systems typically pay for themselves in 3-7 years. Once paid off, the substantial savings generated from the electric generation and gas savings in vehicles provides income at near zero maintenance costs.

Once completed, the value of this system using the current average rate of $0.23 /kwh would be $124.15 B per year – and yet the cost per year of implementation is only $54.2B.

The cost of the energy over this period then drops to $124.15 /kwh, eventually falling to close to $0.008/kwh, the long term cost of maintaining the storage, as the solar generation using silicon PV will last essentially forever.

The savings from gas alone in EVs would generate **$4.32** per day per person. The electric generation value is **$8.67** per day/person. The total value is then **$12.98** per day per person, for an annual total of **$4,738** for every person in California.

These are just the simple economic benefits. The cleaner air, reduction in greenhouse gasses and impact on our environment has a real cost in terms of quality of life and human health, all of which will be vastly improved.

References

Fig 1 California Energy Commission, California Energy Commission Staff, Energy Consumption Data Management System (ECDMS)

Fig 2. Custom Power Solar model with CEC usage data 2016, solar data PVwatts 2.0

Fig 3. Google Project Sunroof

Fig 4. NREL

Fig 5,6,7 Custom Power Solar model with CEC usage data 2018, solar data PVwatts 2.0

Costs of energy storage from:

https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2018/

Vehicle data, natural gas use from California Energy Commission

APPENDIX A

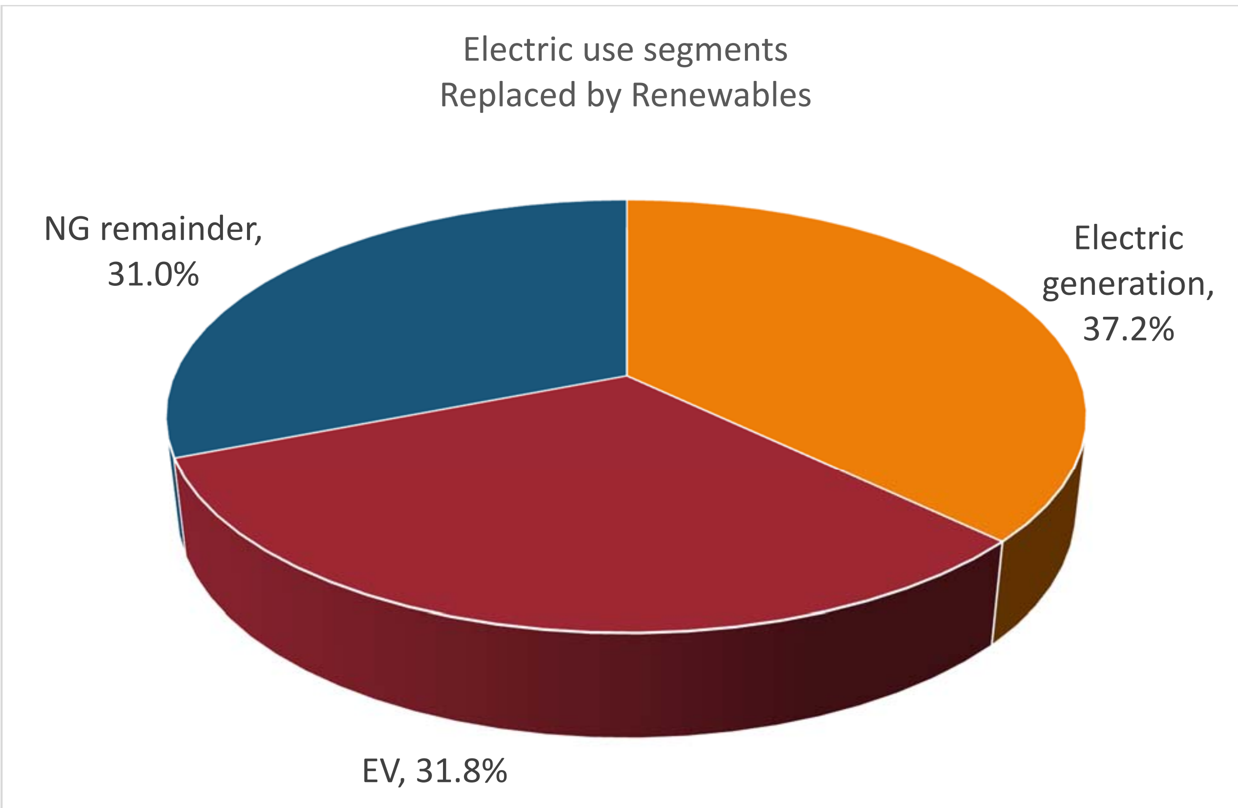

Fig 8. Portions of total generation by type California

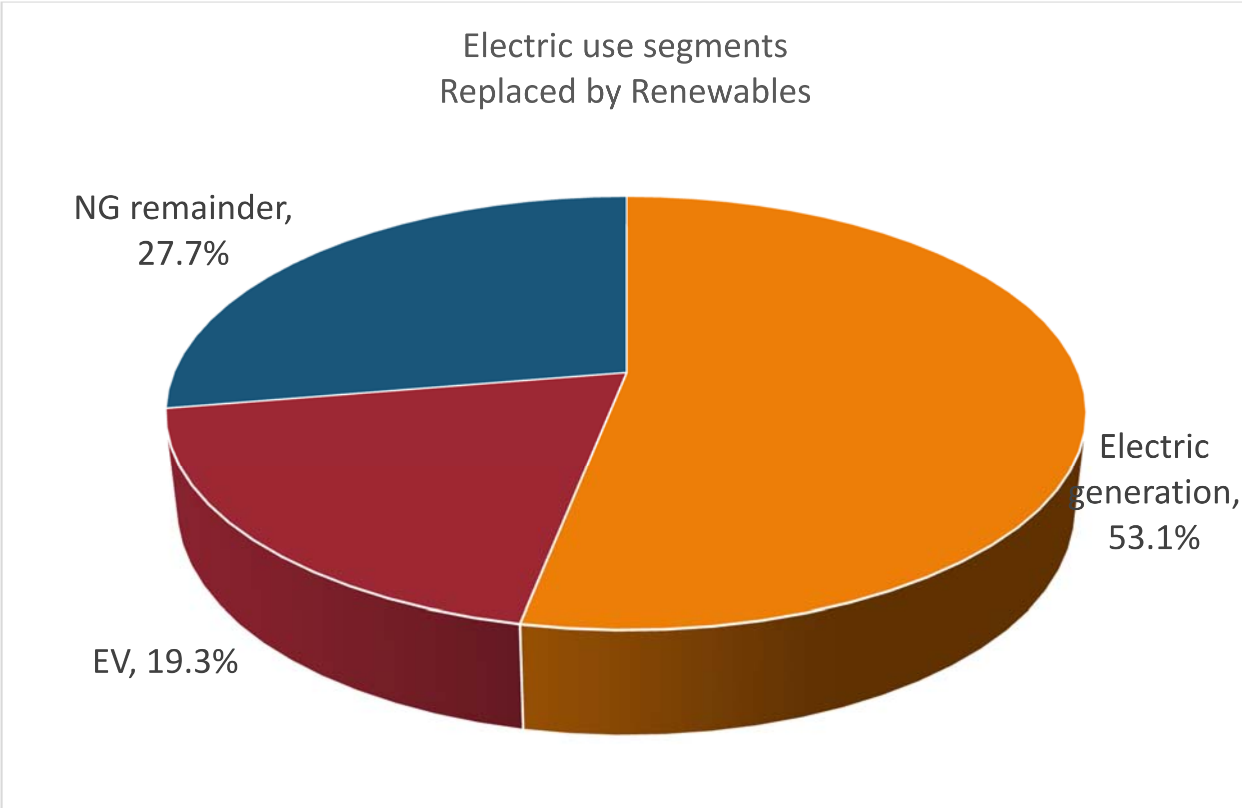

Fig 9. Portions of total generation by type USA

APPENDIX B

BATTERY STORAGE WITH PV

In solar PV systems coupled with battery storage, in general, the amount of storage capacity needed is only the amount needed to get from one day to the next. When solar power exceeds the loads, the excess can be stored back in the battery, and used when the solar power drops below loads.

The above analysis utilized Custom Power Solar' analysis tool, which can model any rate structure and uses the 2017 marginal GHG emissions generated by the state electric utilities and models the 2018 year entire state loads. Solar generation was modeled by averaging 3 regions - Northern California using Oakland solar statistics, Los Angeles, and San Diego. We assumed the grid can distribute power from one region to other. This Excel spreadsheet is over 150Mbytes, so is not included online.

For simplicity, we've included 2 scenarios illustrating the requirements in the accompanying spreadsheet. In the flat load scenario (sheet "Storage flat load"), the load is assumed to be the same 24/7. The amount of time solar is greater than loads varies from winter to summer – dec 21 the amount is 7.75 hr, 3/21 is 10 hours, and 6/21 10.25 hours. The excess power is always more than enough to fill the battery each day, and usually has considerable to spare (normally exported back to the grid). We've normalized the system to a 1 kw solar system (AC) which on average in California generates 1700 kwh/year, so we use a 1700 kwh per year load as a net zero system.

With the average use of 194 watts, then the amount of storage needed in the winter is 3.15kwh, spring 2.72kwh, and summer 2.67kwh. Using the 1kw as the reference allows a simple 1:1 conversion of these values to the ratio of PV to storage capacity needed.

However, few systems have a flat load. The California use is shown in the second example “Storage Ca Load” sheet. Here we see load peaking in the late afternoon, with low demand overnight. This has the fortunate effect of reducing the overall requirement for storage. We’ve calculated the percentage of energy needed based on the CA use scenario which shows then the ratios needed for California use are 2.68 for dec/21, 2.44 for 3/21, and 2.04 for 6/21.

In typical home or business scenarios, these shift even more to low overnight use and higher daytime use, reducing the battery requirements even more.

For the purposes of this study, we’ve used 4 as the PV/storage ratio. In the full annual simulation, we found we needed to increase the over generation to 50%, and the PV/storage ratio to 4, to get 0 days of importing power. With 25% over generation, 23 days of the year imports were needed to cover the differences.

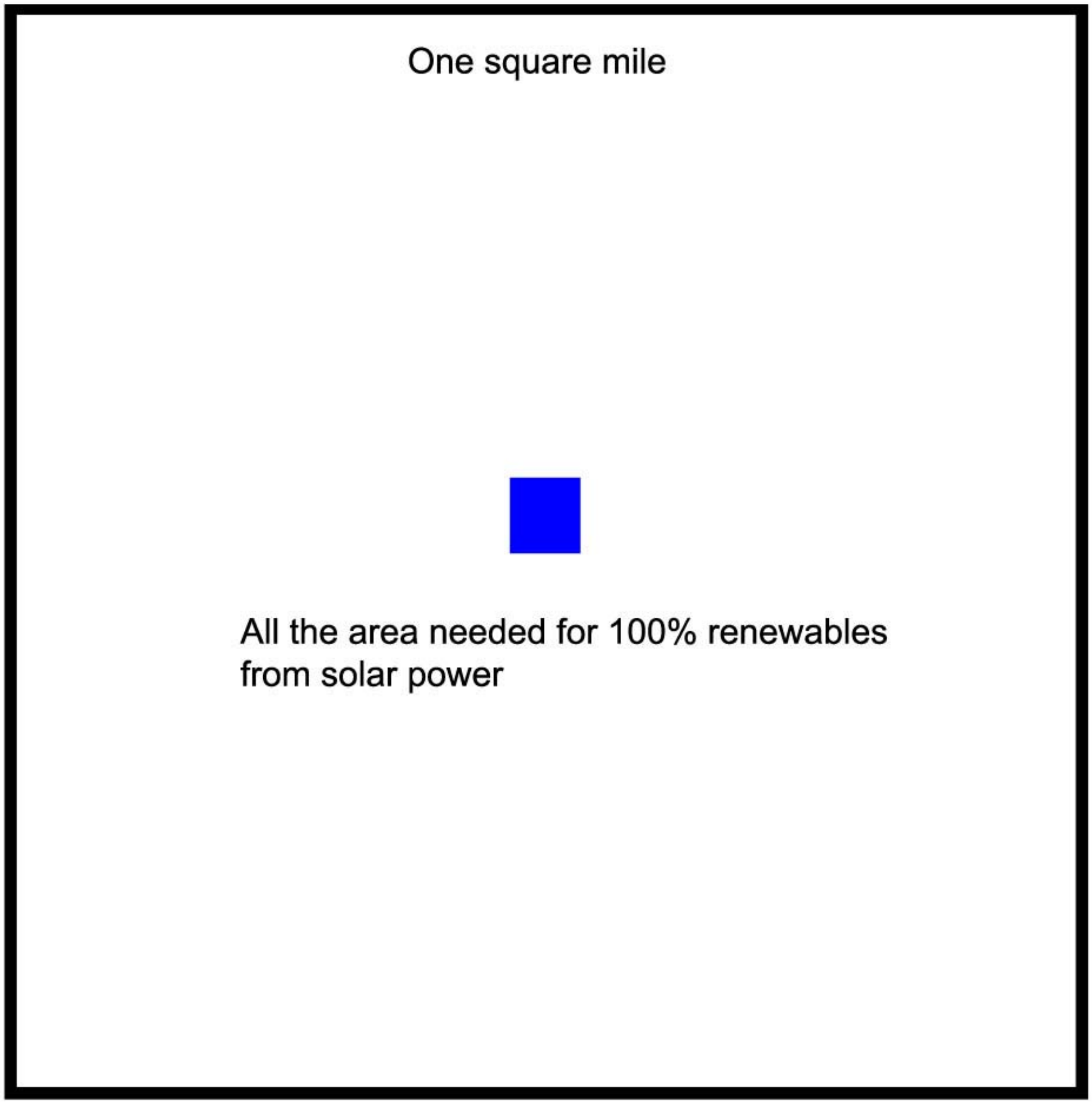

Fig 10. Relative size of solar needed per land area for 100% renewables California = 1.2 acres