Comparative Costs of Geothermal, Solar, and Wind Generation Based on California Independent System Operator Electricity Market Data

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ABSTRACT

Electricity generation data for 2015 were downloaded from the California Independent System Operator’s (CAISO) Open Access Same-time Information System (OASIS) in order to compare electricity generation from geothermal, solar, and wind resources. To investigate project-scale relationships, solar and wind data from the California part of the CAISO control area were scaled to be equivalent to a nominal 30 MW geothermal facility on a megawatt-hours per year basis. Based on the shape of solar and wind delivered throughout the California portion of the CAISO control area during 2015, a 30 MW geothermal baseload (262,800 MWh) is matched by name plate capacity installations of 106 MW and 101 MW, for solar and wind, respectively.

Though large installed MWs of solar and wind provide a MWh equivalent to 30 MW of baseload geothermal, their intermittency results in many hours without adequate generation to meet the hypothetical 30MW demand. For this comparison, when solar and wind are below the required 30 MW, they are shaped with highly efficient combined-cycle gas turbine (CCGT) generation to equal the power output of the 30 MW geothermal facility. Actual shaping of intermittent generation typically requires less efficient gas-fired generation, so the fuel, greenhouse gas (GHG), and unit startup costs used in the analysis are minimums. In addition to the integration, fuel, and GHG costs of managing intermittent solar and wind generation, CAISO’s reported regulation up and down clearing prices are included to represent interval-to-interval management costs. Costs of the CCGT resources needed to integrate intermittent renewables can be accounted for by using estimates of CCGT fixed cost revenue requirements or the levelized cost of electricity (LCOE) of new CCGT that is inclusive of all fuel and operations costs.

Since 30MW baseload generation is being evaluated, any excess generation must be sold on the wholesale market. Costs were assigned to excess generation of solar and wind by comparing a hypothetical power purchase agreement (PPA) price to the CAISO average hourly wholesale price.
This is an incomplete account of the full costs to manage intermittent versus baseload renewable electricity generation, but it provides a minimum basis determined from real data that should be considered when evaluating the complete per megawatt-hour costs of intermittent and baseload resources. When the costs described above are added to a solar or wind PPA contract price of $50/MWh (levelized), the minimum equivalent pricing for a geothermal baseload facility would be $103.12/MWh when compared to solar and $83.28/MWh when compared to wind based on an estimate of the fixed cost revenue requirements of existing CCGT resources. Using LCOE of newly constructed CCGT resources with capacity factor dictated by required shaping to match the hypothetical 30MW demand, the solar-equivalent price is $104.82/MWh, and the wind-equivalent price is $89.50/MWh. If new CCGT generation is utilized at the current California average capacity factor of 51.9% rather than for specifically shaping the hypothetical 30 MW demand, solar- and wind-equivalent costs would be $106.16/MWh and $84.71/MWh, respectively.

Intermittent renewable energy prices do not reflect their cumulative addition to grid management costs nor the real economic costs of CCGT resources required to manage their integration into the real-time electricity demands of customers. Despite ever lower contract prices for solar and wind, California rate payers potentially are bearing the burden of these “hidden” costs of intermittent renewable generation with average EIA-reported retail prices >$150/MWh in 2015 and >$180/MWh at the beginning of 2017. The difference between California’s higher retail electricity prices and those of neighboring states like Nevada is similar on a percentage basis to the difference between solar and wind PPA contract prices and geothermal-equivalent pricing estimated herein.

1. Introduction

CAISO market data are readily accessed online via OASIS (oasis.caiso.com). Reports are available that provide details of the many components that make up the highly complex energy system managed by CAISO. Select data from 2015 were compiled for wind and solar generation, system load and demand, GHG allowance index prices, energy prices, and regulation up and down clearing prices. The data were selected to capture some of the important components required to compare the costs associated with geothermal, wind, and solar generation.

To facilitate the comparison, solar and wind were scaled to a nominal 30MW geothermal project producing 262,800 MWh/yr. The scaling used the 2015 total hourly MWs of solar and wind energy across the entire geographic diversity of the CAISO area within California to define the shapes of hypothetical solar and wind generation of 262,800 MWh in a year. After scaling, the maximum hourly MWs of the scaled data determined the name plate capacities of solar and wind to be installed, 106MW and 101MW, respectively (Figure 1).

2. Methodology

Monthly reports were downloaded via OASIS and compiled into a complete 2015 database that includes wind and solar generation, system-wide forecast demand and load, energy prices, fuel prices, GHG allowance index prices, and regulation up and down settlement prices.
Warren (http://oasis.caiso.com). The data were compiled hourly for the entire CAISO area within California except for daily GHG allowance index prices and monthly natural gas prices. Total

![Figure 1: 2015 CAISO wind and solar generation scaled to be equivalent to 30 MW geothermal baseload.](image)

Seasonal changes and inherent intermittency cause solar and wind to be less than or greater than the 30 MW baseload at the scale of hours, days, weeks, and months.

CAISO reported MWhs of solar and wind generation, 13,187,743 MWh and 8,760,137 MWh, respectively, were scaled to a year total of 262,800 MWh, equivalent to a nominal 30MW baseload (Figure 1). The required capacity to be installed was determined by the maximum hourly MWh values of the scaled data. The scaled solar and wind data are compared to a nominal 30 MW geothermal facility with hourly output varying from 27 to 31 MW due to ambient temperature changes associated with time of day and time of year. Figure 2 schematically illustrates the various components of generation and demand that go into the comparison of baseload and intermittent renewable resources.

The amount of energy needed to augment the solar and wind so that their output matches the 30MW geothermal facility was determined by subtracting the solar and wind generation from the hourly geothermal output for every hour solar and wind were less than geothermal. For each hour requiring augmentation, the required additional MWs were multiplied by a CCGT heat rate of
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7.655mmBtu/MWh (U.S. EIA, 2016) and by the monthly gas price to arrive at a fuel cost. Each required additional MW was converted to 800 lbs of CO$_2$, converted to metric tonnes, and multiplied by the daily CAISO GHG Allowance Index Price to arrive at a GHG cost. A once daily 1400 mmbtu startup cost (CAISO, 2016), resulting in additional fuel and GHG costs, was assessed for any day that the gas shaping requirement went to zero, i.e., solar and wind provided a minimum of 30 MW, since CCGT resources would be shut down if not required and need to be started the next interval that solar and wind did not meet the 30 MW demand. The total hours requiring augmented MWs divided by total hours of the year determined a capacity factor for the CCGT generation specific to shaping of the hypothetical 30 MW demand.

For each hour the solar and wind generation exceeded the geothermal output, the geothermal output was subtracted from the solar and wind output to determine excess generation. Costs were assigned to excess generation of solar and wind by comparing a hypothetical PPA price to the CAISO average hourly wholesale price. The price difference between a hypothetical $50/MWh (levelized) PPA and the hourly average wholesale price was used as a proxy for excess generation cost, i.e., the amount paid per the PPA that is above the real-time CAISO price. The hourly upward and downward changes in excess generation were multiplied by CAISO hourly regulation downward and upward clearing prices to provide a cost for interval-to-interval management of intermittency. Costs of the CCGT resources required to shape solar and wind were assessed in two ways, fixed cost revenue requirements and LCOE. As described above, required CCGT generation was determined by subtracting the solar and wind generation from the

Figure 2: Schematic illustration of the components used to compare baseload and intermittent renewable generation
hourly geothermal output for every hour solar and wind were less than geothermal. The required CCGT MWs were multiplied by $18.84, the $/MWh estimated fixed cost revenue requirement determined by CAISO (2016), to arrive at the cost of CCGT resources. For comparison, the required CCGT MWs were also priced with respect to LCOE (Lazard, 2016; $48/MWh at 80% capacity). LCOE was scaled in two ways, one matching the capacity factor necessary to shape the hypothetical 30 MW scenarios (55% to back up solar, 34% to back up wind) and the other matching the reported average capacity factor of California CCGT resources, 51.9% (Nyberg, 2015).

The aforementioned costs were summed for the year and divided by 262,800 MWh to arrive at a cost per MWh for the 30MW scenario considered (Table 1). For the CCGT fixed cost scenario, geothermal equivalent price was determined by adding to the hypothetical $50/MWh (levelized) PPA the costs of fuel, GHG, excess generation, start up, regulation up and down, and CCGT fixed costs. For the CCGT LCOE scenarios, geothermal equivalent price was determined by adding to the hypothetical $50/MWh PPA the costs of excess generation, regulation up and down, and LCOE scaled to either the implied capacity factor or the California average of 51.9% (Nyberg, 2015).

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\begin{array}{|l|c|c|}
\hline
\text{Cost Item} & \text{Solar} & \text{Wind} \\
\hline
\text{Resource and Market Management} & $/\text{MWh} & \\
\hline
\text{CCGT Shaping Fuel} & $16.14 & $9.78 \\
\text{CCGT Start-up (1400MMbtu)} & $7.23 & $5.08 \\
\text{CCGT Shaping GHG Allowance Index Price} & $2.66 & $1.67 \\
\text{$50/MWh PPA minus wholesale} & $13.86 & $8.72 \\
\text{CAISO regulation up and down} & $2.49 & $1.32 \\
\hline
\text{CCGT Resources} & $/\text{MWh} & \\
\hline
\text{CCGT $18.84/MWh fixed cost revenue requirement} & $10.75 & $6.71 \\
\text{CCGT implied capacity factor LCOE} & $66.75 & $82.50 \\
\text{CCGT Average CAISO LCOE} & $69.08 & $69.08 \\
\hline
\text{Equivalent Geothermal Price ($/\text{MWh})} & \text{Solar} \quad \text{Wind} \\
\hline
\text{CCGT fixed cost revenue requirement} & $103.12 & $83.28 \\
\text{CCGT implied capacity factor LCOE} & $104.82 & $89.50 \\
\text{CCGT Average CAISO LCOE} & $106.16 & $84.71 \\
\hline
\end{array}
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Table 1: Summary of costs for comparison of 30MW geothermal generation to equivalent MWh of solar and wind generation modeled after 2015 CAISO data

3. Results

As described above, per MWh costs were determined by summing each class of costs for the year and dividing by the hypothetical 262,800 MWh of total generation for the year. Based on 2015 prices reported by CAISO, the average fuel costs of gas shaping solar and wind are $16.14/MWh and $9.78/MWh, respectively. Using CAISO’s daily GHG Allowance Index
prices, the average emissions costs of gas shaping solar and wind are $2.66/MWh and $1.67/MWh, respectively. Based on the estimated fuel requirement of 1400 MMbtu for CCGT startup (Rhyne et al., 2015), the costs of required startups are $7.23/MWh and $5.08/MWh for solar and wind, respectively. Inefficiencies in fuel use and impacts on GHG associated with non-optimal operation of CCGT resources are intentionally ignored, so the actual fuel and GHG costs are underestimated, potentially by a large percentage.

The differences between the hypothetical PPA price of $50/MWh (levelized) and the hourly CAISO wholesale price for hours during which solar and wind generated in excess of 30 MW are $13.86/MWh and $8.72/MWh for solar and wind, respectively. The partial costs of intermittent energy management based on CAISO’s hourly reported regulation up and down clearing prices are $2.49/MWh and $1.32/MWh for solar and wind, respectively.

The costs of CCGT resources with respect to LCOE adjusted to reflect the implied capacity factor required to shape solar (CCGT at 55%, $66.75/MWh) and wind (CCGT at 34%, $82.50/MWh) into a 30MW baseload are $38.47/MWh and $29.46/MWh for solar and wind, respectively. California’s CCGT fleet currently operates at an average capacity factor of 51.9% (Nyberg, 2015), which corresponds to an LCOE of $69.08/MWh and solar and wind equivalent costs of $39.82/MWh and $24.67/MWh, respectively. An estimate of the real costs of CCGT shaping with existing CAISO generation resources using a reported fixed cost revenue requirement of $18.84/MWh are $10.75/MWh and $6.71/MWh for solar and wind, respectively. LCOE is inclusive of all costs, whereas the revenue-requirement costs do not include fuel, startup, and GHG costs.

Solar-and wind-equivalent prices for geothermal generation based on the fixed cost revenue requirements of existing CCGT resources used for shaping are $103.12/MWh and $83.28/MWh, respectively, including costs of having the CCGT available, its fuel, GHG, excess generation, start up, and regulation up and down. If new CCGT resource costs are based on LCOE that is scaled to the capacity factors implicit in shaping the 30MW solar and wind scenarios (55% to back up solar, 34% to back up wind), solar- and wind-equivalent geothermal prices are $104.82/MWh and $89.50/MWh, respectively, including costs of excess generation and regulation up and down. If LCOE is scaled to the average capacity factor of California’s CCGT fleet, 51.9%, then solar- and wind-equivalent geothermal prices are $106.16/MWh and $84.71/MWh, respectively.

4. Conclusions

The integrated costs of solar and wind based on the assumptions used herein are at least $103.12 for solar and $83.28 for wind, but the actual costs could easily be higher. While this analysis produced relatively high actual costs for wind and solar, this is an incomplete account of the full costs to manage intermittent versus baseload renewable electricity generation; however, it provides a minimum basis determined from real data that can be considered when comparing per megawatt-hour costs of intermittent and baseload resources. Notably, these underestimated costs correspond to solar- and wind-equivalent geothermal prices higher than recently reported for geothermal PPAs. Development of geothermal resources in the Western USA has slowed due in part to the difficulty securing PPAs that support new developments. The equivalent pricing suggested herein likely would have a positive impact on some projects.
Intermittent renewable energy prices in a $/MWh PPA, as is usually executed, do not reflect their cumulative addition to grid management costs nor the real economic costs of gas-fired resources required to manage their integration into the grid. An important management component excluded from this analysis is the cost of managing maximum daily net load ramps. The intermittent resource MWhs in the 30 MW scenarios would contribute to the CAISO system net load ramping requirements, adding up to 106 MW to the amplitude between highs and lows of the “duck curve.” Lower net loads lead to more likely periods of excess generation, and over time, prices will lower and be increasingly negative to help mitigate the discrepancy between supply and demand. As prices on average go lower, the price difference between intermittent PPA and wholesale will increase, raising the equivalent geothermal prices evaluated herein. As net load ramping requirements increase with penetration of intermittent renewables, gas-fired resources operate at incrementally lower capacity factors and lower efficiencies, the costs of which are not fully captured here. The LCOEs for gas-fired resources will go up as capacity factors go down, adding to the gas-fired resource costs as they are further displaced by intermittent renewable resources, further raising the equivalent geothermal prices. Batteries and other storage systems are being added to help mitigate issues related to intermittent renewables, and they currently have $/MWh costs significantly higher than any discussed herein (Lazard, 2015). CAISO is likely to treat these as “system costs” when in reality they are wind and solar costs, and they are not needed to manage geothermal power additions to the system.

In addition to not fully accounting for all costs, the comparison herein also ignores potential value added with baseload geothermal versus intermittent generation. Depending on the location of the project and the off taker(s), geothermal generation adds value where it can contribute to capacity and reliability requirements. Typical, long-term contracts for geothermal power sales reduce risk related to fuel and carbon prices, and consistent baseload geothermal generation is insulated from trends of increasing negatively priced intervals and the risk of economic and system curtailments.

Geothermal baseload lessens the overall requirements for and impacts of gas-fired generation that supports intermittent resources, and it is important to understand the ramifications of amounts and types of back up required to integrate intermittent resources. For example, though decreasing use of gas-fired generation would seem ideal for reducing GHG, simple-cycle gas-fired plants required to quickly respond to intermittency are less efficient and more polluting than the CCGT analyzed herein. Based on heat rates reported by EIA and assuming a constant load, a 24-hour-365-day CCGT emits less CO$_2$ than an intermittent renewable resource backed up by a simple-cycle gas-fired plant that must operate >67% of the time, i.e., backing up intermittent resources with capacity factors <32%. Neither solar nor wind have achieved capacity factors >30% in California.

Despite ever lower “apparent” contract prices for solar and wind generation, California rate payers are bearing the burden of the “hidden” costs of intermittent renewable generation with an average retail price >$150/MWh in 2015 and >$180/MWh in early 2017 (U.S. EIA, 2017). The difference between California’s higher retail electricity prices and those of neighboring states like Nevada is similar on a percentage basis to the difference between solar and wind PPA contract prices and geothermal-equivalent pricing estimated herein. The rate payers potentially are done a disservice when baseload renewable generation is not the first piece maximized within a renewable portfolio. In contrast to California, though having less aggressive RPS goals,
Nevada is ahead of the RPS goals they have set, have retail electricity prices 50% less than California, and their renewable portfolio is comprised of 69% geothermal (U.S. EIA, 2017). The contrast in consumer experiences in California and Nevada combined with the sizeable difference in percent geothermal making up the renewable portfolios should serve as an important lesson for those building renewable portfolios for the future.

REFERENCES


