

Effects of PV on Conventional Generation

Rajatha Bhat¹, Miroslav Begovic¹, Insu Kim¹, John Crittenden²

¹*School of ECE, ²Brook Byers Institute for Sustainable Systems, Georgia Institute of Technology*

Abstract

In 2010, photovoltaic generation accounted for 0.28 percent of the renewable generation mix in USA. It has recently been growing at an annual rate of over 220 percent [9]. The proliferation of PV systems offers opportunities (such as a reduction in peak load and loss) but also potential for use in Volt/Var management and control. It also creates need for additional generation that covers uncertainty involved in PV output. In fact, they may in some cases increase fossil fuel consumption (compared to not using renewables with rapid output changes) because of their intermittency. In addition, viewed in hourly resolution (averaged every hour), the PV system has a stable output. Rapid variations in short-term PV generation, typically in minute-averaging resolution, result from transient weather changes. Therefore, this study models the short-term intermittency and investigates the impact that it may have on operation of thermal resources intended to complement the renewables.

1. Introduction

Increasing penetration of wind and solar energy in the electric energy generation mix are raising concerns among electric system operators because of the variability and uncertainty associated with the power sources. One of the main concerns with the integration of high penetrations of wind and solar generation is the effect their variable nature can have on the system. Unit commitment and scheduling are performed over days to meet the forecasted load requirements. Power demand exhibits sudden wide excursions over short intervals of time. The ability to respond to such fast changes in demand and price of energy can be quite rewarding. This provides the incentive to utilize the generation ramping rates beyond traditional elastic limits [5]. During shorter periods of time (minutes), the system re-dispatches its units to counteract deviations from the schedule through load following. These deviations are particularly frequent because of the intermittent nature of renewable sources. Traditional units are re-dispatched to perform regulation, which is the fast response of generators to changes that range from seconds to minutes. Through these steps, the power system operator is able to maximize the use of cheap base load units (e.g., nuclear

or coal-fired generators) while utilizing fast-response units (e.g., gas combustion turbines) to maintain system stability and reliability. Thus high penetrations of renewable generation results in a need for more flexible generators, with fast ramping capabilities. In this study, only PV renewable energy is considered. Additional considerations should be made for other types of stochastic generations resources, like wind.

Economic dispatch has traditionally been a process by which the load demand is met by power generation mix from available resources such as nuclear, hydro, and thermal power plants in a fashion that minimizes cost of fuel and emissions. Fuel cost is affected not only by the instantaneous power output but also the rate of change of power from one instant to the next. This change of power is known as the ramp rate of the thermal power plant. Therefore, a more accurate fuel cost model would also consider the ramp rates [8]. Based upon the duration of each ramping, the corresponding ramping cost will be determined. However, in order to select a proper ramping process in generation scheduling, the ramping cost should be considered in the optimization process. There is a trade-off between the ramping cost and the amount of generated energy. A higher ramping rate, which relates to a more expensive ramping, can generate more energy. The suitable generation schedules are obtained based upon balancing the costs of ramping and energy generation [8].

Renewable sources are penetrating the grid increasingly by the day. While this has benefits in the form of reduced load demand from conventional sources, it also has drawbacks. The main one being the unpredictability and rapid variations in generation. Conventional generators must be flexible enough to account for these rapid fluctuations. This flexibility in generations is expressed in terms of ramp rates. However, up and down ramping of generators results in fatigue, thereby shortening the useful life of the generator. Cycling refers to the operation of electric generating units at varying load levels, including on/off, load following, and minimum load operation, in response to changes in system load requirements. Every time a power plant is turned off and on, the boiler, steam lines, turbine, and auxiliary components go through unavoidably large thermal and pressure stresses, which cause damage. This damage is

made worse for high temperature components by the phenomenon called creep-fatigue interaction [2]. Another factor to consider is the emissions from conventional generators as a result of ramping. This has been discussed in [13] and [14]. [13] models a wind or solar photovoltaic plus gas system using measured 1-min time-resolved emissions and heat rate data from two types of natural gas generators, and power data from four wind plants and one solar plant. Over a wide range of renewable penetration, CO₂ emissions were found to achieve ~80% of the emissions reductions expected if the power fluctuations caused no additional emissions. Using steam injection, gas generators achieved only 30-50% of expected NO_x emissions reductions.

[14] assess the implications on long-run average energy production costs and emissions of CO₂ and some pollutants from coupling wind, solar and natural gas generation sources. The study utilizes five-minute meteorological data from a US location that has been estimated to have both high-quality wind and solar resources, to simulate production of a coupled generation system that produces a constant amount of electric energy. Coupling wind energy with a natural gas turbine can potentially reduce long-run average production costs, although incrementally adding photovoltaics to the portfolio increases costs. The coupled wind/gas system has higher NO_x emissions than simply running a natural gas turbine at a constant level of output, but lower CO₂ emissions. Adding photovoltaics reduces the CO₂ emissions profile of the system slightly while increasing the NO_x profile.

While the impact of renewable integration on emissions is an important factor to be accounted for, it is beyond the scope of the study presented in this paper.

Ramp rates of generators are generally specified within elastic range of the strength of the shaft to safeguard the rotor from fatigue. These limits can, however, be exceeded, albeit at the risk of reducing the rotor life. Such effects on the rotor life can be compensated by incorporating appropriate ramping costs [5].

In most analysis, the objective is to minimize a quadratic cost function, without considering ramp rates. In this study, ramping costs are considered as a part of the objective function which is then minimized by optimization tools to provide the most economic dispatch of available generation. This improves accuracy.

2. Modeling of PV Generation

In order to assess the intermittency of PV generation and estimate the short-term, typically minute-by-minute, changes of PV systems, it is necessary to study the high resolution data, for which the data is becoming publicly

available. One study, to generate high-resolution solar data, used probability distribution models [10], [11]. Another study proposed that a probability distribution model was not appropriate for modeling the statistical intermittency of high-resolution solar radiation, so it presented a simple Markov Chain Monte Carlo (MCMC) algorithm for random sampling that approximated the desired distribution [12].

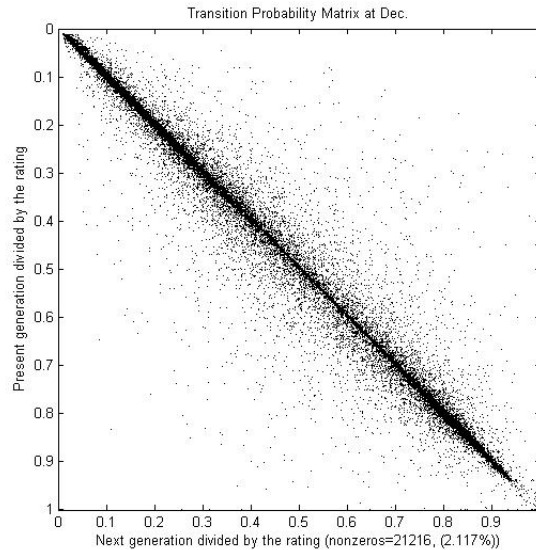


Fig. 1. Transition probability matrix for a short-term intermittency of PV output obtained from NREL observation data.

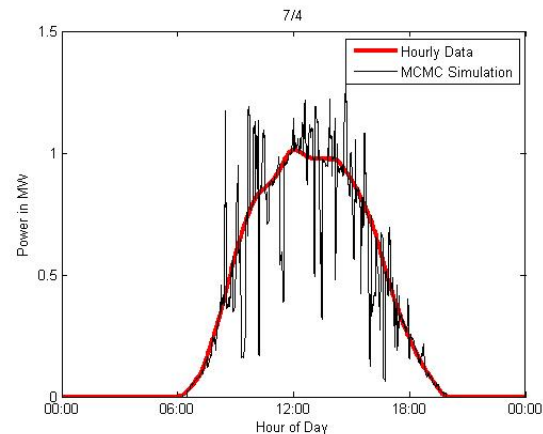


Fig. 2. Hourly (red) and minute (black) resolution PV output data for a day with strong variations in insolation.

The following tasks are needed to develop a high resolution model of PV output:

- (1) Parameterization of the distribution of the short-term intermittency of PV.
- (2) Construction of the transition probability matrix using the solar data collected from multiple test sites.
- (3) Estimation of the generation of the dispersed PV

systems using the first-order MC method, and analysis of their effects in minute resolution from the perspective of energy, especially for peak power and the spinning reserve, the costs of generating electricity, and emissions.

Fig. 1 demonstrate the diagonal dominance (but also presence of outliers indicating rapid changes in output) of transition probability matrix of PV output obtained from 8,8 million data points in NREL observation study. The matrix is sparse (only 2.117% nonzero elements). Fig. 2 shows the discrepancies between hourly and minute resolution in PV outputs on a day when the intermittency is pronounced.

3. Generation Allocation

The goal of this paper is to study the cost effects that increased penetration of PV has on the system operation. Therefore, some assumptions have been made which do not affect the results of the analysis to a great extent. In this study, the problem of unit commitment has not been considered. It is assumed that all available units are ON at all times of operation. A single coal generating unit and single aggregated gas unit are assumed to constitute the non-nuclear part of the thermal generation mix. This gas turbine is used to follow the load and is assumed to have fast ramping capability.

Three levels of PV penetration are considered : 10%, 20% and 30%. The simulations have been done for one peak day of the year. The same analysis can be applied for other days to get the overall yearly cost. Nuclear is assumed to be a constant base load that has zero ramping. Nuclear, hydro and PV generation are considered as negative loads and the dispatch is run for coal and gas generators to meet the load demand. While coal also has load following capabilities, it is very expensive to increase the ramping rate of a coal fired generator. The coal fired small and large units are the expensive load following units undergo significant damage due to change in operations. Typically, large power plants are operated at baseload and do not cycle much [2]. Therefore, an upper ramping limit of 0.005 to 0.006 pu has been imposed as a limitation on the coal generator. An actual daily load curve is used for the numerical analysis in minute resolution.

4. Cost Model

The fuel cost model from [3] is used here. A ramping rate cost term is added to the conventional quadratic cost function. A higher penalty is given for a higher

increasing ramp rate when compared to a decreasing ramp rate. The fuel cost model is :

$$f_{Coal} = aP_{Coal}^2 + bP_{Coal} + c$$

$$f_{Gas} = aP_{Gas}^2 + bP_{Gas} + c + d \frac{dP_{Gas}}{dt}$$

Here the first three terms are identical as in the conventional quadratic function of output, but the contribution of the output ramp rate is added as the last term. Factors a, b, c, and d are calculated by the least square method applied to real data. The factor d is identified in the power increasing and decreasing stages separately, because it takes on a different value depending on whether the output is increasing or decreasing [3]. A ramp rate constraint 'd' has not been applied on coal generation, as the ramp rate of coal is never allowed to exceed 0.5% (Coal generator does not vary rapidly) and therefore no ramping penalty is imposed on coal generator.

| | Coal | Gas |
|----------|-------------------------------------|--|
| a | 0.000023 | 0.000082 |
| b | 0.194991 | 0.068454 |
| c | 3.162663 | 11.90857 |
| d | Ramp Rate Constraint not considered | 0.030004(Power Increasing) 0.018842(Power Decreasing) |

Table 1: Typical a,b,c and d parameters for Coal and Gas

The optimization function is as mentioned above, subject to constraints such as total generation equal to the load demand. The cost of various types of generation is assumed from a variety of sources, not with an intent to provide accuracy, but rather to illustrate the impact of intermittency on the operational costs. For coal and gas generation, the cost is obtained directly from the cost functions upon optimization. The cost of nuclear is assumed as \$6.6/MWh, while that of PV is \$145/MWh. Hydro generation is considered to have zero cost for the purpose of this study.

5. Results and Figures

1. 0% PV Penetration

As can be seen in Figure 2, in the absence of large scale PV output excursions, the output of the gas turbine is fairly smooth and does not need to be frequently ramped up and down. The maximum generation of the gas turbine is about 39.31% of its maximum capacity.

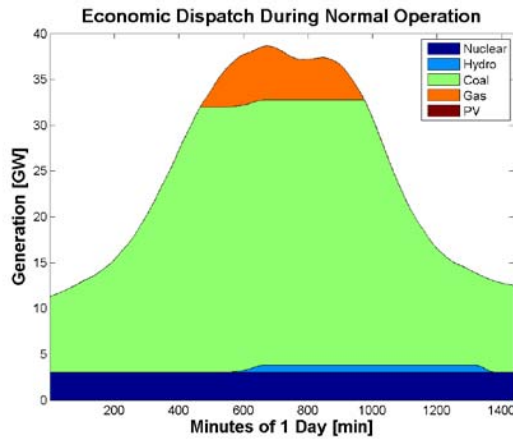


Fig. 3: Economic Dispatch for 0% PV Penetration

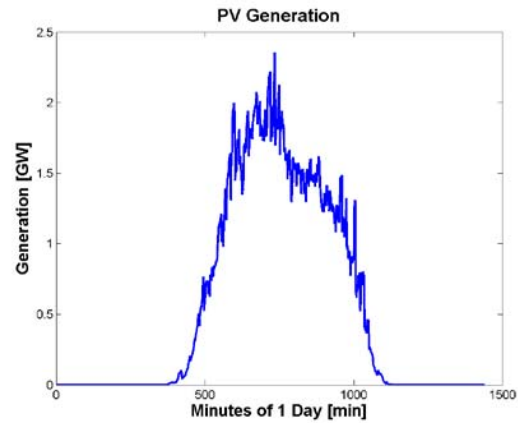


Fig. 6: PV generation for 10% PV Penetration

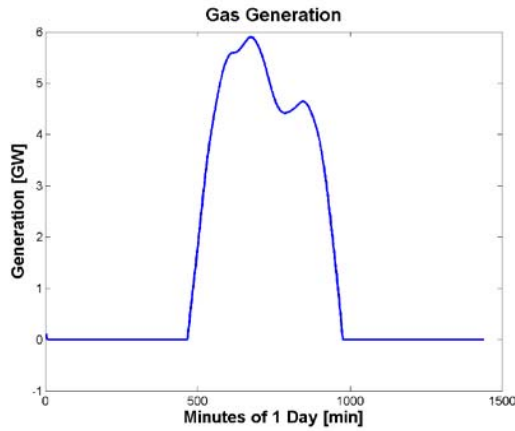


Fig. 4: Gas generation for 0% PV Penetration

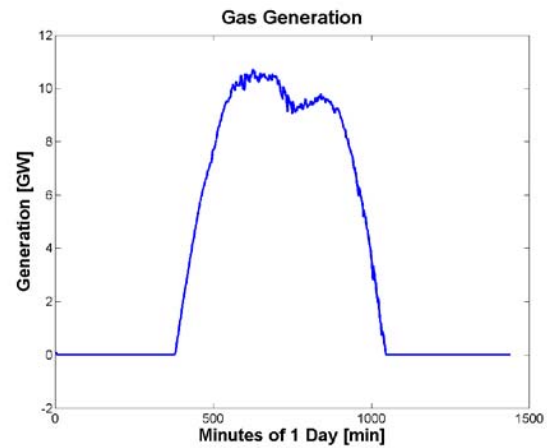


Figure 7: Gas generation for 10% PV Penetration

2. 10% PV penetration.

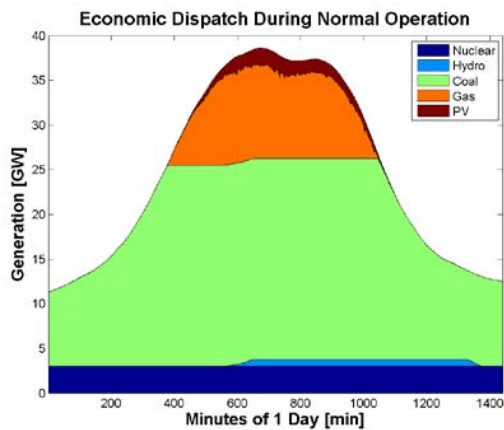


Figure 5: Economic Dispatch for 10% PV Penetration

When generation mix of the entire system is assumed to consist of additional PV systems with the aggregate capacity equal to 10 percent of the annual peak load, the output of the gas turbine is not as smooth as before and exhibits more pronounced ramping. Whenever the PV output is low, gas turbine has to ramp up and meet the deficit in generation. Similarly, when the PV output is high, the gas turbine has to ramp down to balance the load. Also, the output of coal generator has to be reduced so that it does not violate its ramping constraints. Therefore, at higher PV penetrations, coal output reduces and gas output increases as it is more flexible. Increase in more expensive gas output along with the cost of PV causes an increase in overall cost. Maximum generation of the gas turbine is about 68.09% of the maximum capacity.

3. 20% PV Penetration.

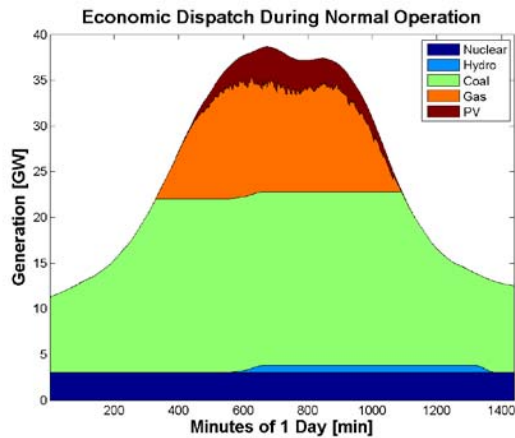


Fig. 8: Economic Dispatch for 20% PV Penetration

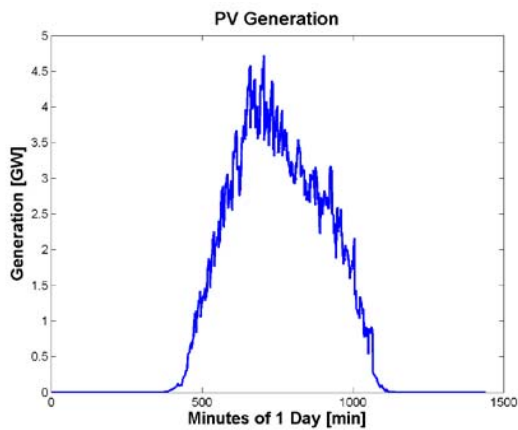


Figure 9: PV generation for 20% PV Penetration

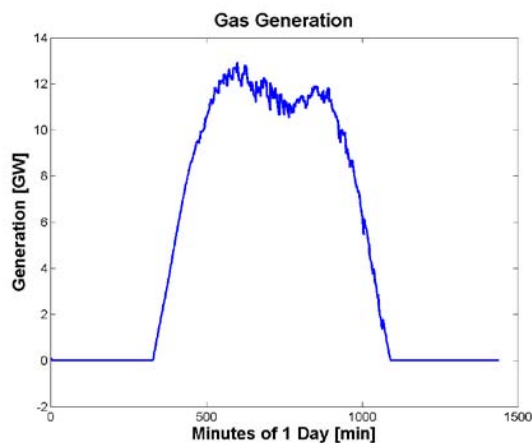


Figure 10: Gas generation for 20% PV Penetration

When PV generation capacity doubles (to 20 percent of the annual peak load), there is a further increase in the ramping rate of the gas turbine due to an increase in PV penetration. Coal output also reduces as it is not a flexible source of generation. This, as before, results in an increase in gas generation, which combined with cost of PV, causes an increase in overall cost. The maximum generation of the gas turbine is about 79.33% of the maximum capacity.

4. 30% PV Penetration.

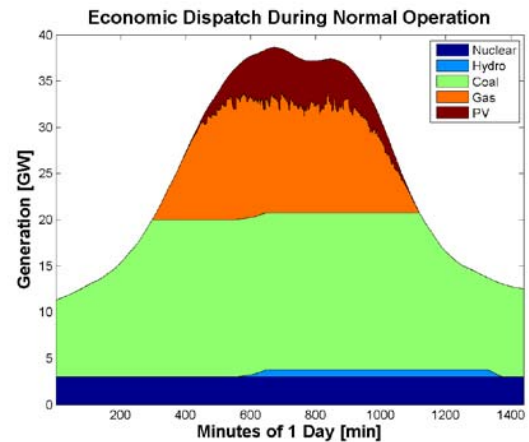


Figure 11: Economic Dispatch for 30% PV Penetration

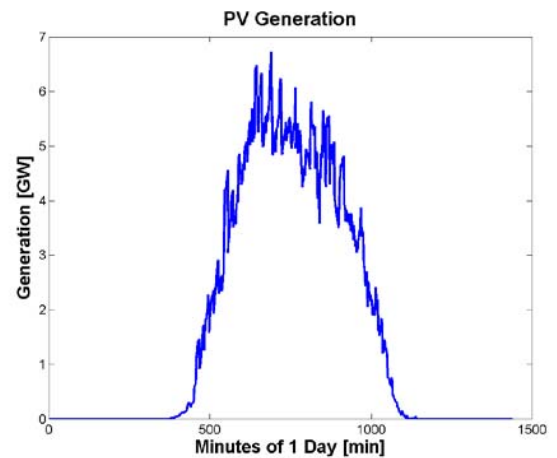


Figure 12: PV generation for 30% PV Penetration

Finally, at triple the PV capacity (30 percent penetration), there is a further increase in the ramping rate of the gas turbine due to an increase in PV penetration. There is a small reduction in coal generation

as it cannot keep up with the rapidly fluctuating demand. Due to the costs of increased gas and PV, there is an additional increase in overall cost. The maximum generation of the gas turbine is about 90% of the maximum capacity.

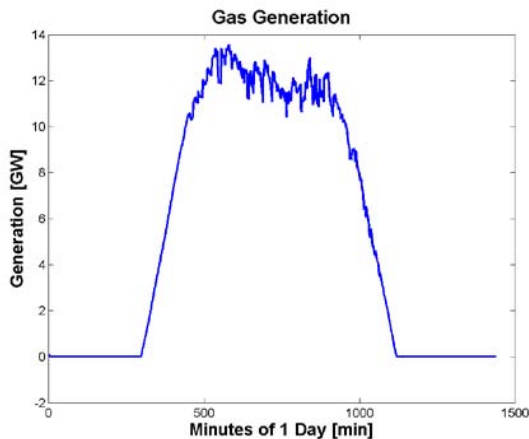


Figure 13: Gas generation for 30% PV Penetration

Obviously, the ramp rate is the highest for highest PV penetration (30 percent). The relative costs of ramping can be visualised in the form of a bar graph in Fig. 15. The costs of coal, gas and ramping are shown in the form of a stacked bar graph Fig. 16. Compared to the cost of fuel, ramping costs are relatively small, but overall costs are growing fast with additional PV capacity deployment.

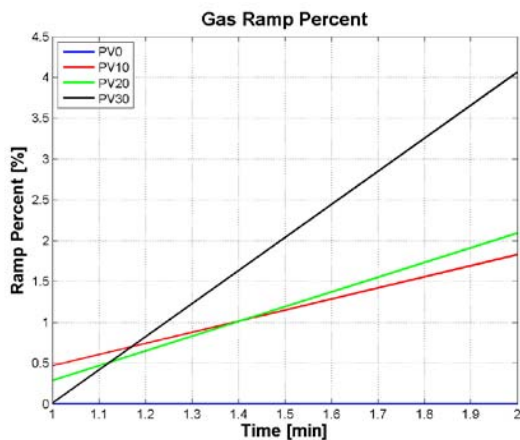


Figure 14: Ramp Rates of Gas turbines for varying levels of PV generation (shown here at peak ramping levels).

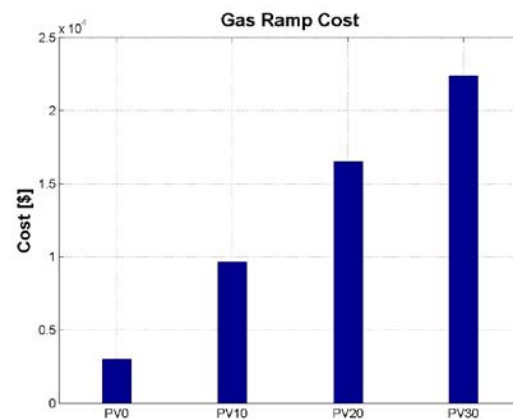


Figure 15: Daily cost of ramping of gas turbines for varying levels of PV generation.

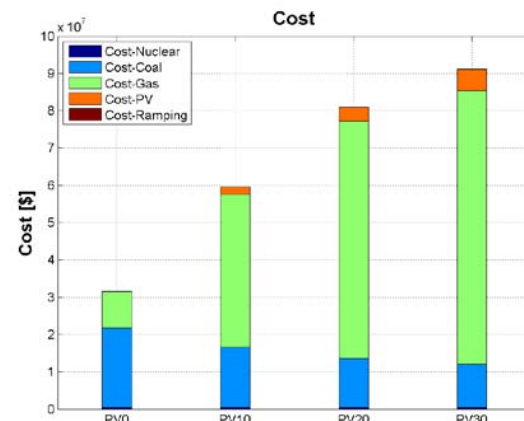


Figure 16: Stacked Cost of different generation types for the system with varying levels of PV generation

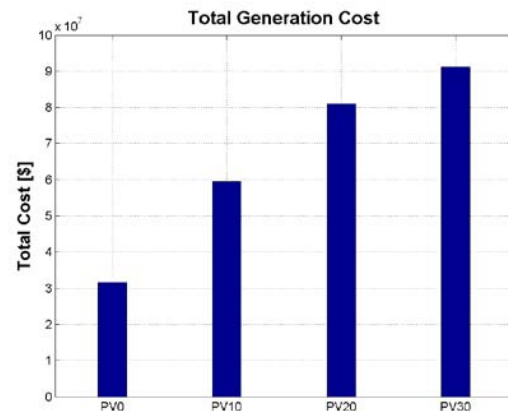


Figure 17: Total Cost of Generation for varying levels of PV generation

As can be seen in the graphs, increase in PV causes a significant increase of the ramping costs. It also causes an increase in overall cost because PV is an expensive

source of power, and increased penetration causes increase in gas generation as well thereby adding to total cost.

| PV Penetration(%) | Ramping Cost (\$/day) | % Ramping |
|-------------------------------------|-----------------------|-----------|
| 0 | 3020 | 0 |
| 10 | 9680 | 6.96 |
| 20 | 16529 | 12.94 |
| 30 | 22390 | 13.06 |
| Maximum Gas (% of Maximum Capacity) | Total Cost (\$/day) | |
| 39.31 | 31,516,000 | |
| 68.09 | 59,546,000 | |
| 79.33 | 80,965,000 | |
| 90 | 91,138,000 | |

Table 2: Comparative costs of the four scenarios indicate significant increase in usage of gas capacity.

In the example presented, no upper limits were imposed on the ramping of gas. However, the median ramp range is about 20% [2]. This puts a limitation on the amount of generation at every instant leading to a situation where the demand may not be met by the resources available. In such cases, there is a need for spinning reserve to make up for the shortage in generation.

Spinning reserve is the unused capacity which can be activated on decision of the system operator and which is provided by devices which are synchronized to the network and able to affect the active power [1]. Different utilities calculate spinning reserve differently.

1. California ISO

The ISOs requirement for Spinning Reserve is 50% of the Operating Reserve (OR) requirement. This requirement is equal to 5% of the Demand to be met by generation from hydroelectric (hydro) resources, plus 7% of the Demand to be met by generation from other resources, plus 100% of any Interruptible Imports, or the single largest contingency (if the latter is greater). The calculation for the OR requirement is as follows:

$$OR = \max(OR_1, OR_2) + 100$$

Where: OR_1 = a percentage (5%) of hydro generation scheduled plus a percentage (7%) of generation from other sources. OR_1 is computed separately for each SC based on its load and hydro generation schedules and then summed up over all SCs to determine the OR_1 for each congestion zone, and the whole system.

OR_2 = MW loss due to most severe contingency. OR_2 is computed system-wide as the maximum of the following for each hour [6]:

- Operator-entered value for each zone and for each hour
- Largest generating unit for each hour
- Largest net tie import to the ISO control area for each hour

The cost of spinning reserve is around \$10/MW [6]. Therefore, the cost of spinning reserve would have to be added to the cost calculations.

2. Georgia Power

Georgia Power is committed to keeping a spinning reserve capacity that can be immediately called on in case of an unplanned steam plant or nuclear plant shutdown equal to the capacity of the largest unit (presently 1,100 MW). Hydro capacity is ideal spinning reserve because it can be fully loaded in one to two minutes in response to demand [7]. Fuel cost of generation of hydro power is zero and therefore would little affect the overall generation cost.

6. Conclusions

From this analysis we can conclude that increased penetration of distributed generation has significant impact on the generation outputs of conventional sources. Increasing variable renewable generation on the electric grid has resulted in increased cycling of conventional fossil generation. In this example, cycling of gas turbine increased and the output of coal generator reduced. The inclusion of these costs in economic load dispatch simulations results in increased costs and reduced reliability of conventional generation due to cycling. Increased cycling may have a significant life-shortening impact on the turbines [2]. Increasing PV penetration significantly increases the overall generation costs as well as cycling costs. This is under the assumption that the power system provides the total of its own active power balance. Increased penetration of PV increases the cost but reduces resource consumption. However, cycling allows for the system to deliver a wider range of energy and include renewable generation. A natural consequence of these considerations would be to consider a multifaceted approach to managing intermittency in the systems with large penetration of renewables, using not only load following, but also demand response, both in the form of involuntary (conservative voltage reduction), and voluntary incentive programs which would need to be designed to provide sufficient incentives to the participants so as to generate enough interest while keeping the overall costs low enough not to exceed the cost of alternative solutions.

7. Acknowledgement

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