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Very Large-Scale Deployment of Grid-Connected Solar Photovoltaics in the United States: Challenges and Opportunities

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P. Denholm and R. Margolis

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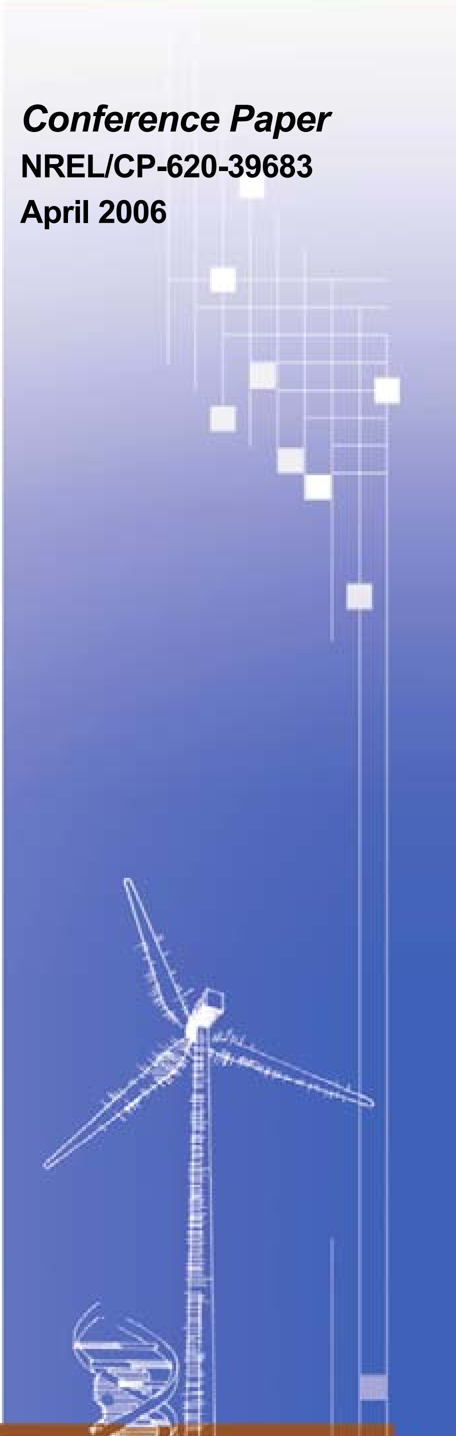

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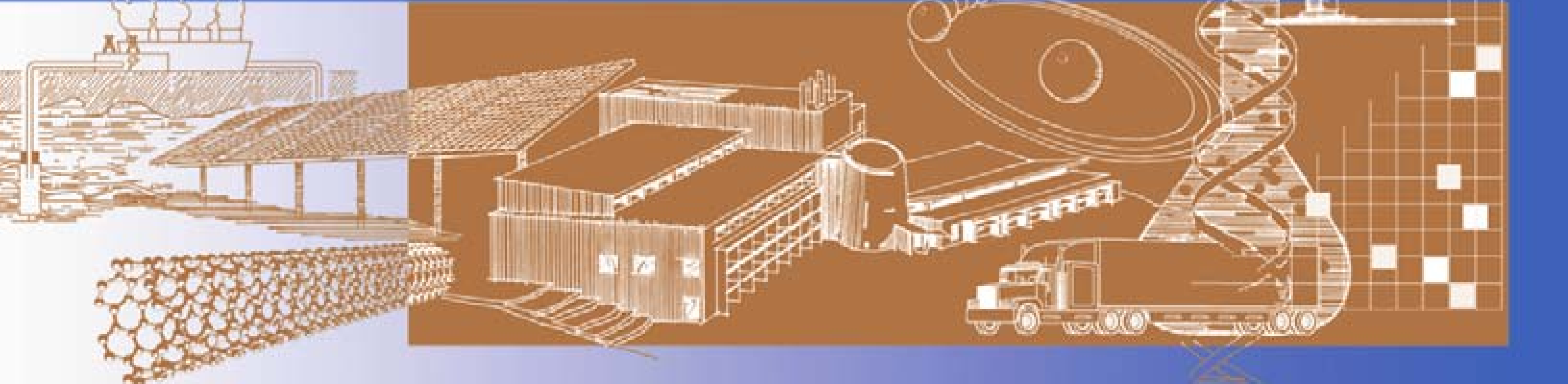

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VERY LARGE-SCALE DEPLOYMENT OF GRID-CONNECTED SOLAR PHOTOVOLTAICS IN THE UNITED STATES: CHALLENGES AND OPPORTUNITIES

Paul Denholm
National Renewable Energy Laboratory
1617 Cole Blvd
Golden, CO 80401
paul_denholm@nrel.gov

Robert M. Margolis
National Renewable Energy Laboratory
901 D. Street SW, Suite 930
Washington, D.C. 20024
robert_margolis@nrel.gov

ABSTRACT

In this paper, we analyze the potential for solar photovoltaics (PV) to be deployed on a very large scale and provide a large fraction of a system's electricity. We explicitly examine how the hourly availability of PV interacts with the limited flexibility of traditional electricity generation plants. We find that under high penetration levels and existing grid-operation procedures and rules, the system will have excess PV generation during certain periods of the year. This excess PV generation results in increased costs, which can increase dramatically when PV provides on the order of 10%-15% of total electricity demand in systems that are heavily dependent on inflexible baseload steam plants. Measures to increase penetration of PV are also discussed, including increased system flexibility, increased dispatchable load, and energy storage.

1. INTRODUCTION

The technical potential of the grid-connected solar PV market in the United States is enormous – potentially more than 500 GW in rooftop applications, or many TW, including ground-based systems [1]. Not only does PV have a larger technical potential than any other renewable energy technology, it also is not as geographically constrained as other renewables. In theory, PV has the potential to supply all of the electricity demand in the United States, and to virtually eliminate carbon emissions from the electric power sector. The intermittency of solar PV, however, presents a set of critical challenges with respect to integrating PV on a very large scale into the electricity grid. Ultimately, this intermittency may limit the potential contribution of PV to the electricity sector. In this paper, we examine the potential technical limits on PV penetration, considering not only the limitations of the solar resource, but also the limitations of existing generators to accept the variation in PV generator output.

2. INTERACTION OF PV WITH ELECTRIC POWER SYSTEMS

Traditional electric power systems use a combination of generator technologies to meet the system's total electricity demand. In the United States, a large fraction of total demand is met by large baseload plants. These plants are typically in excess of 500 MW each and generate electricity using steam created by coal or nuclear fuels. The daily variations in demand are met largely by cycling plants, typically smaller coal plants, steam or gas turbine plants fueled by natural gas, and hydroelectric plants [2].

Solar PV is not dispatchable in a traditional sense, meaning its output cannot be controlled and scheduled to respond to the variable consumer demand for electricity. It does, however, have the advantage of providing output that has considerable coincidence with natural demand for electricity, driven largely by daytime activities – particularly in the summer when a large amount of electricity is used for air conditioning [3]. Deploying solar PV effectively reduces the amount of "conventional" generation required from traditional generation plants.

Figure 1 demonstrates the potential impact of this effective demand reduction on the total generation requirements of an electric power system. In this case, we have superimposed the simulated output of a large PV system on the actual recorded load for the Electric Reliability Council of Texas (ERCOT) system in the year 2000 [4]. The PV system is ~16 GW (peak AC output) , and would provide about 11% of the total system demand, strictly on an energy basis. The two days shown in Figure 1 (June 1 and 2) indicate significant benefits and "usefulness" of PV. There is a large amount of energy produced by PV on these days, and this production is highly coincident with demand – the PV output has occurred near the peak demand, reducing both the need for capacity, as well as the emissions and fuel use associated with lower efficiency peaking plants.

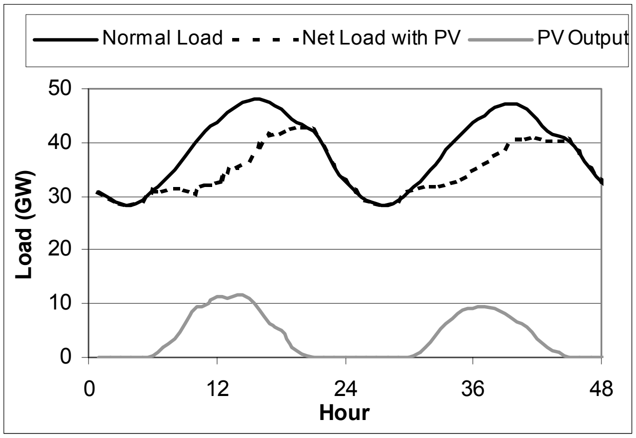

Fig. 1: System Load With and Without a Large (16 GW) PV System on Two Summer Days

Examining another period of the same year with the same simulated PV system yields different results. As shown in Figure 2, on these two days (March 11 and 12), moderate temperatures reduce total HVAC electricity demand; neither large amounts of space heating nor cooling is required. Moderate electricity loads and excellent solar insolation, particularly on March 11, produce a dramatic drop in the net demand for electricity. The minimum net demand of ~10 GW in the simulated system is well below the normal annual minimum demand of ~18GW.

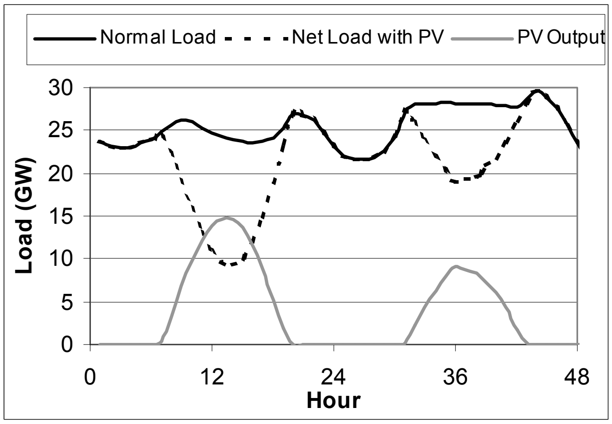

Fig. 2: System Load With and Without a Large (16 GW) PV System on Two Spring Days

The drop in demand in the middle of the day presents specific technical challenges for a utility operator. First, all generators, especially large baseload plants, have limits to the rate at which they can ramp up or down. Even ignoring this constraint, there are fundamental limits to how much baseload plants can reduce output, particularly if they need to increase output a few hours later. Nuclear plants are particularly limited by long ramping times and limited ability to reduce output [5]. Coal plants are generally more flexible, but still have minimum output requirements due to flame stability and a number of other operational issues [5]. If plant output needs to be reduced below this minimum load, it may need to be completely shut down, requiring a costly and potentially lengthy restart process. Given the relatively short window of high PV output, it is unlikely that these plants will be able to respond to the reduced demand illustrated in Figure 2.

Each individual plant has its own maximum "turndown" flexibility, and the overall system minimum output is the aggregated minimum output of each individual plant. We are aware of no firm guidelines establishing the minimum turndown rate on individual plants or utility fleets; but an examination of wholesale prices provides some insight into when minimum loading conditions occur in electric power systems. Several regions of the United States have established wholesale energy markets, with historical data now available [6,7]. Prices are typically correlated with load, largely reflecting the variable cost of fuel and efficiency of units "at the margin." (This is a greatly oversimplified explanation, but discussion of wholesale power markets is beyond the scope of this paper.) Examining prices during periods of low demand reveals that prices can fall below the variable operational cost of a coal-fired power plant; prices can even fall to below zero during periods near the annual system minimum demand. There are a number of reasons why the price of electricity can drop below the actual cost of generating electricity, depending on both the location and current system conditions – but one important reason is based on minimum loading. Utilities are strongly motivated to keep plants above their minimum load levels and keep plants running to avoid costly shutdown and start-up expenses [8]. The costs of selling electricity below the costs of producing it (and even paying consumers to take it sometimes) reflects these technical limitations on large baseload plants.

To avoid interference with baseload plant operations, utilities would likely reject the output from PV generators. This situation is similar to the manner in which wind turbines are occasionally shut down during periods of low demand and high winds in the Danish electric power system. Otherwise, utilities would need to find some other use for this energy, or change the fundamental operation of their power system to accommodate PV generation. To consider how much PV could be used in a traditional system, and to evaluate options for increasing PV penetration, we developed a model to analyze the impacts of large-scale PV deployment.

3. MODELING THE IMPACTS OF LARGE-SCALE PV DEPLOYMENT

We developed a model (PVflex) that can compare simulated solar output to actual load, and calculate the "usable" PV generation under a user-specified level of system flexibility. The model requires both recorded solar insolation data and recorded load data for at least one year, preferably from a reasonably large utility region. We obtained recorded hourly load data from the ERCOT system, [4] which provides most of the electricity for the state of Texas. We also obtained hourly recorded global horizontal insolation data for nine spatially diverse sites in Texas for the same year (2000) [9]. In addition to data availability, ERCOT is a good case study due to its good solar resource, and the fact that it is an isolated electrical grid with limited capacity for imports or exports. The insolation data for each site was converted to AC electrical output using HOMER, a publicly available tool that contains an algorithm to convert global horizontal radiation measurements into PV output [10]. Large-scale PV deployment will likely require a variety of PV orientations (including utility-scale tracking arrays), so we assumed the following mix of systems: 15% flat, 10% south facing at 10-degree tilt, 15% south facing at latitude tilt, 10% southwest facing at 10-degree tilt, 10% southwest facing at latitude tilt, 20% single axis tracking, 20% two-axis tracking. We also assumed a uniform distribution of PV systems among the nine sites.

The total aggregated PV output from the 63 location-orientation combinations (9 sites x 7 orientations) was then scaled to produce a simulated PV output of any desired size. The PVflex tool iteratively steps through a series of net PV system sizes in an attempt to generate up to 50% of the system's total energy from PV. For each PV system size, the hourly PV output is subtracted from the normal electricity load. If the net load with PV falls below the minimum loading point, all PV output that produces a net load less than the minimum loading point is considered "spilled" and effectively unusable. PVflex calculates both the average spilled PV, and the marginal spilled PV.

We set the minimum system turndown rate for our base case simulation at 35% of peak load. This value is roughly equal to the annual minimum normal load for the ERCOT system in 2000. The wholesale price of electricity during hours of minimum load are often at or below the actual production cost of electricity, which implies a system at or near minimum turndown for the baseload generator fleet. This number (35%) is by no means definitive, and the sensitivity of PV penetration to minimum loading is discussed in Section 5.

4. RESULTS

Using a minimum turndown rate equal to 35% of peak load, some PV generation becomes surplus when PV is providing about 4% of total annual electricity demand. This amount of "surplus PV" increases non-linearly with increasing PV deployment, and results in a reduced effective capacity factor (CF) for PV. The base capacity factor for the entire simulated PV system is 22.3%, based on the system's peak AC rating.

Figure 3 illustrates the drop in system capacity factor as a function of PV penetration on an energy basis.

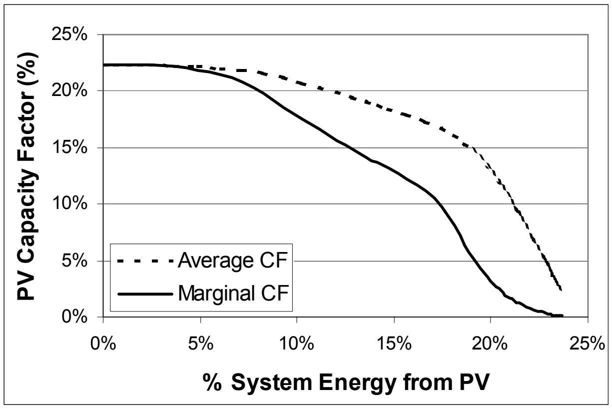

Fig. 3: PV System Capacity Factor as a Function of PV Energy Contribution

The cost impacts of this reduced capacity factor can also be calculated because the levelized cost of energy from a PV system (excluding O&M) is proportional to 1/CF. Figure 4 illustrates the relative cost of PV for the simulated case. We have used relative cost here to emphasize the shape of the curve, rather than absolute values. If so desired, the reader may assume any "base" cost of PV generated electricity and simply multiply this "base" cost by the relative cost to estimate absolute costs at a given penetration level.

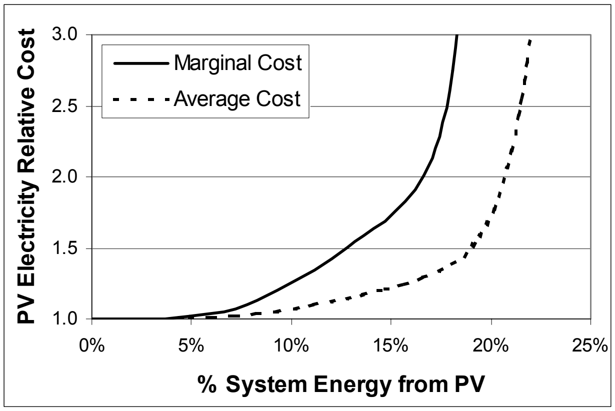

Fig. 4: Relative Cost of PV Generated Electricity as a Function of PV Energy Contribution

Based only on minimum loading constraints, it is not possible to define a “maximum” penetration of PV. The limits on PV will be determined by economics, based on the value of PV to an individual, utility, or society as a whole. In Figure 3, we cut off the cost at 3 times the base cost, largely because the cost slope of PV is approaching vertical, implying very little additional system-wide benefits of further installed PV. For example, at a PV energy contribution of about 17%, the “spill rate” of the next unit of installed PV is above 75%, providing a relatively small amount of usable energy to the system.

5. DISCUSSION: OPTIONS TO INCREASE PV PENETRATION

To move beyond the limits illustrated in Figures 3 and 4, we must investigate options to increase the usefulness of PV during periods of low normal demand. One obvious solution is to increase the overall flexibility of conventional generation. Figure 5 demonstrates the impact of increased system flexibility. Here, we repeated the analysis in Figure 4, but we decreased the system minimum loading from 35% to 20% and 0% of annual peak demand.

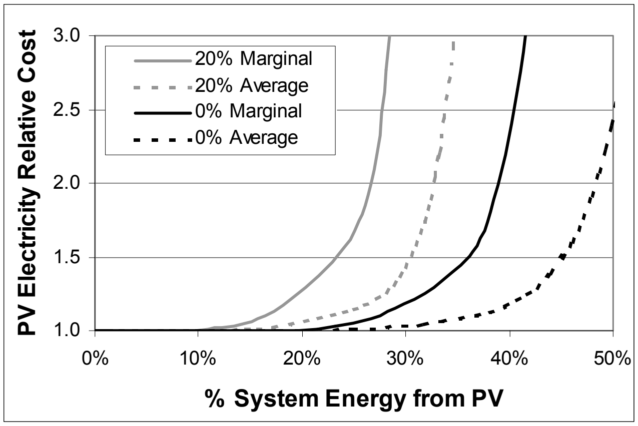

Fig. 5: Effect of Increasing System Flexibility on the Relative Cost of PV

By increasing the system flexibility, it now becomes at least theoretically possible to provide 50% of the system’s energy from PV – although this requires the ability to completely turn off all conventional generation for short periods of time without cost penalty. However, even in this extreme system flexibility scenario, the marginal cost of PV at 50% PV contribution is about 18 times that of the base cost.

Increasing system flexibility is one of several possible approaches to increasing the economic penetration of PV. We can consider these other approaches under the context of the installed capacity needed to reach the limits of intermittent PV generation.

Figure 5 illustrates the PV capacity required to achieve high levels of PV system contribution under a range of minimum system loading constraints. Three curves are shown, reflecting the three different system minimum loads considered in our analysis: 35%, 20%, and 0%.

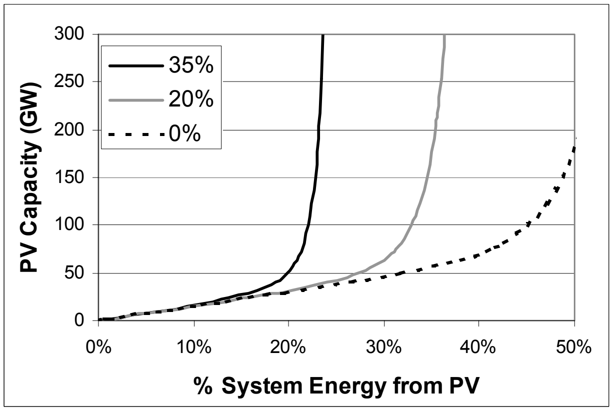

Figure 6: PV Capacity Requirements to Achieve Large Contribution to Total Energy Demand

In Figure 6, deviations from the linear relationship between PV capacity and PV energy contribution indicates the spilled energy and unusable capacity resulting from limited baseload-generator flexibility. The deviation at the low level of flexibility (35% minimum turndown) occurs at about 5 GW (this is the point where the capacity factor of PV begins to drop in Figure 3.) Given that global PV production in 2004 was roughly 1 GW [11], it will clearly take decades to reach this level of market development in Texas and or other states in the United States. (Of course, load growth will require an even greater amount of PV before intermittency-related impacts are realized.) The amount of time needed to achieve this level of penetration may allow for appropriate changes in the electric power system.

There are a number of possible technologies that would enable increased use of PV. Dispatchable load is one possibility, including "dual-fuel" appliances such as water heaters and space heaters. These appliances could switch from natural gas to electricity during times where the price of electricity drops due to a large surplus of PV generation. Another potential source of dispatchable load is "plug-in" hybrid electric vehicles, which could benefit from midday charging after morning commutes. Of course, energy storage represents the "ultimate" solution to the problems of intermittency. Not only could energy storage absorb the excess PV generation, but it could also aid in increasing the overall flexibility of electric power systems by decreasing dependence on traditional baseload generation. Ultimately, it is likely that a combination of technologies will provide the most economically attractive solution to address the limits of intermittent energy sources such as solar PV.

6. CONCLUSIONS

Traditional electric power systems are designed in large part to utilize large baseload power plants, with limited ability to rapidly ramp output or reduce output below a certain level. The increase in demand variability created by intermittent sources such as PV presents new challenges to increase system flexibility.

Current electric power systems that are dominated by large baseload thermal-steam generators may require rejection of large amounts of PV generation when this intermittent source provides between 10-15% of a region's electricity. However, the time required to achieve this level of PV penetration provides many opportunities for utilities to increase system flexibility or deploy PV-enabling technologies. We found that increasing the flexibility of the electric power system in the simulated system could increase the contribution of PV to perhaps 20%-30%. Beyond this contribution, enabling technologies such as fuel switching in "smart" appliances, dispatchable load from plug-in hybrid or other electric vehicles, or stationary energy storage would be required to enable very high levels of PV contribution to the electric power system. Given the long lifetimes of many electricity generation technologies, now is the time to begin thinking creatively about ways to begin moving toward a more flexible and PV-friendly electric power system.

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