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The Effect of Large Scale Transmission Limitations on Renewable Energy Load Matching for the Western U.S.

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WREF2012: THE EFFECT OF LARGE SCALE TRANSMISSION LIMITATIONS ON RENEWABLE ENERGY LOAD MATCHING FOR THE WESTERN U.S.

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ABSTRACT

The variability of wind and solar energy technologies is perceived as a major obstacle to employing otherwise abundant renewable energy resources. Based on the available geographically dispersed data for the Western U.S. (excluding Alaska), we analyze the extent to which the geographic diversity of these resources can offset their variability. First, we determine the best match to loads that can be achieved with wind power and photovoltaics with no transmission limitations and then impose large-scale transmission limitations to capture regional specifics of load matching with renewables.

Without energy storage and assuming unlimited energy flows between regions, wind and PV can meet up to 80% of loads in the Western U.S. while less than 10% of the generated power is curtailed. Limiting hourly energy flows by the aggregated transmission line carrying capacities decreases the fraction of the load that can be met with wind and PV generation to approx. 70%. The fraction of curtailed energy does not increase with the onset of transmission limitations.

NOTATION

C_t – the amount of curtailed wind and/or PV energy at hour t

F_{tmn} – power flow (MW) from region m to region n at hour t

f_{mn} – aggregated power lines capacity (MW) between regions m and n, sets transmission limitations

G_t – dispatchable generation from conventional sources at hour t

g – upper bound on WECC dispatchable generation capacity (MW)

l_t – hourly load (electricity consumption) over the WECC area

P_j – fraction of the maximum potential built capacity at the PV site j

p_{jt} – the input generation that could be produced at hour t by the PV resource at site j

WECC - Western Electric Coordinating Council; here we consider only the continental U.S. territory, excluding Alaska

W_i – fraction of the maximum potential built capacity at the wind site i

w_{it} – the input generation that could be produced at hour t by the wind resource at site i

INTRODUCTION

There are abundant solar and wind resources in the United States – enough to provide more than 10 times the annual U.S. electric load [1]. In spite of this, there are concerns that these technologies cannot supply a significant portion of U.S. generation needs.

Although various technical challenges connected with wind energy [2,3] are being solved, claims have been made that, due to variability, solar and wind power technologies must be heavily, if not completely, backed up with conventional generation capability and/or storage; in other words, the capacity value (i.e. how much conventional generation capacity can be replaced by a unit of renewable generation capacity) of wind and solar is low [4]. We employ new solar and wind resource data at the hourly level that are available for tens of thousands of sites across the country. These data allow us to estimate the value of spreading the deployment of wind and solar plants out to take advantage of the fact that solar and wind availabilities vary geographically, not just temporally.

The integration of significant amounts of wind and solar power in an energy system poses multifaceted challenges [4,5]. This is not the first paper to analyze the advantages of using geographically diverse resources of both solar and wind to better meet load [6,7]. The present study focuses on the hour-to-hour variations of demand and generation at tens of thousands of potential wind and solar sites throughout the year in the United States. This paper expands our prior findings [8] by exploring the effect of energy transfer constraints imposed by current electric grid in the Western Interconnect (WECC). Clearly, it is not practical to account for the details of connecting every potential wind or solar generation site to the existing grid. It is possible, however, to account for large scale transmission limitations in an aggregated power grid that represents net power flows between regions [9].

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APPROACH

We examine a year of hourly data with thousands of possible sites of both solar and wind. We also do not rely on uncertain present or future cost estimates for these technologies.

This work does not answer all the questions on this issue. It provides only a practical upper bound on the contribution from wind and solar power because:

1) the method considers only large scale transmission constraints, it does not account for the detailed electric grid stricture, and it does not consider contingency or reserves requirements
2) sites are selected only on the basis of their ability to contribute energy and supply it to the load hubs, not costs
3) optimization is conducted based on one year's historical resource and load data and has not undergone testing against data from other past years.

Many of these will be the subject of future work. Nonetheless the results to date tell an important story.

Our method answers the following question: What is the best match to loads in the Western U.S. that could be achieved with wind power and photovoltaics? We measure the accuracy of the match in terms of capacity and generation that would be required from backup dispatchable[2] generators in order to meet all loads throughout the year.

We have built the Renewable Energy Load Matching model (RELM), with primary decision variables being where and how much wind (W_i) and photovoltaic (P_j) resource should be built at each wind and PV site (indices i and j respectively). Had we used costs for technologies and fuels, we could have minimized the electricity cost. However, since future fuel and technology costs are so uncertain, this model that doesn't have to consider costs gives a robust result independent of cost.

Wind and solar generation are utilized solely on the basis of how well they meet load; not their relative economics. In our linear program, the first constraint is that the load (l_t) is met. The wind and solar sites are selected by the model to minimize the dispatchable generation (G_t) along with curtailments (C_t). The minimization of either the required thermal capacity or energy losses effectively gives some recognition to the cost of capacity and energy.

$$\text{Minimize } \sum_t [\, G_t + C_t] \qquad (1)$$

Subject to

$$l_t + C_t = \sum_i W_i * w_{it} + \sum_j P_j * p_{jt} + G_t \quad \text{for all t} \qquad (2)$$

$$0 \le W_i \le 1 \quad \text{for all i} \qquad (3)$$

$$0 \le P_j \le 1 \quad \text{for all j} \qquad (4)$$

w_{it} is the generation that could be produced at hour t by the wind resource at site i (w_{it} is an input), and p_{jt} is the generation that could be produced at hour t by the photovoltaic resource at site j (p_{jt} is an input). Both w_{it} and p_{jt} are inputs; thus a perfect forecast throughout the year is assumed.

Expression (1) gives the objective function, (2) sets the condition that all the loads should be met, (3) and (4) set a cap on how much resource can be built at each potential wind or solar site. As a rule, the names for model variables are designated with uppercase letter, while constant parameters begin with lowercase.

Expressions (1-4) define the optimization for the entire Western U.S. with no transmission limitations. To include large scale transmission limitations, we used the following methodology.

First, in the model, the Western U.S. territory is divided into 35 regions. We use the same regions as in the Renewable Energy Deployment System model (ReEDS).[3] No transmission limitations are considered within region boundaries, and aggregated transmission lines [9] represent power flows between regions. Within each region m, expressions (1-4) are applied, the difference being that indices i and j span only the potential generation sites in the region and regional load l_{tm} is corrected to account for transmission line flows to (F_{tnm}) and from (F_{tmn}) the region:

$$l_{tm} + C_{tm} = \sum_i W_i \cdot w_{it} + \sum_j P_j \cdot p_{jt} + G_{tm} + \sum_n F_{tnm} - \sum_n F_{tmn} \quad \text{for all t and m} \qquad (5)$$

$$|F_{tnm}| < f_{nm} \quad \text{for all t, n and m} \qquad (6)$$

$$\sum_m \max_t(G_{tm}) \le g \qquad (7)$$

[2] Here, we call dispatchable generators those that can be used when needed. They would include the standard set of conventional plants (e.g. coal, gas) as well as storage technologies (e.g. pumped hydro and batteries), and a subset of renewable electric technologies (e.g. biomass, geothermal, hydro). They would exclude wind and photovoltaics which are not dispatchable due to their variable resources.

[3] http://www.nrel.gov/analysis/reeds/

Expression (5) sets the load matching constraint for each region, (6) sets the transmission limitations due to line carrying capacities,[4] and (7) limits the sum over all regions of dispatchable generation capacities $\max_t(G_{tm})$.

Here again, the wind and solar sites are selected solely on the basis of their contribution to meeting load, i.e. their relative costs are not considered. This model also gives equal weight to dispatchable generation and losses of energy through curtailments.

INPUT DATA

The wind and PV data for the WECC and a large part of the eastern U.S. have only recently become available. For the wind resource, we use data developed for the Western Wind and Solar Integration Study (WWSIS) [10][5]. The distinguishing characteristics of these data are that they include three years of generation information (2004 – 2006) for 32,000 potential wind sites in the western U.S. in ten minute intervals[6] over the course of each year (http://wind.nrel.gov/Web_nrel). The nominal generation capacity at wind sites in the database is 30 MW.

For the photovoltaic resource, we use hourly insolation data for the same years for 250 western sites found in the National Solar Radiation Data Base [11][5] and converting that to power generation from a south-oriented PV panel with a 10° tilt using the PVWatts model[7]. The NSRDB does not provide estimates of the maximum amount of PV capacity that could be installed at each site. However, to prevent unreasonable overuse of the sites that have generation profiles that best match load profiles, we limited the PV capacity at any single site to 1 GW.

The load data were aggregated from Ventyx's Velocity Suite product, which is based on hourly historical demand for the same years from FERC Form 714 Part III Schedule 2.

RESULTS

Large scale transmission limitations effects on wind and solar load matching in WECC are summarized in Table 1. The table compares cases with and without transmission limitations. As reported earlier [8] for the no transmission limitations case and also shown in the table, about 80% of the load can be matched with wind and solar, while curtailing less than 10% of the generated energy. Surprisingly, the existing electric grid[8] imposes only marginal limitations on these numbers. With a 7% increase (from 88 to 95 GW)[9] in dispatchable generation capacity, about 70% of the WECC load can be met with wind and solar while complying with large scale transmission limitations.

This result suggests that the current transmission grid is not overbuilt (since it does impose restrictions, although small, on the amount of wind and solar that can be built into the system), and at the same time it is capable of supporting large temporal and regional variations in generation. An interesting feature of energy transmission is that the net sum of transmission flows over the system positively correlates with both dispatchable generation and curtailments (the correlation coefficients are 0.17 and 0.22 respectively).[10] This may be interpreted as the system moving power from where it is cheaper to where it is more needed – the result is not as straightforward if we recall that there are no costs in the formulation of the problem (1, 3-7).

Finally, the geographic distribution of the optimal generation sites is also affected by transmission limitations. Fig.1 compares optimal wind sites selection for the cases with and without transmission limitations. While similar, the two cases (Fig.1a and 1b) have important differences. The transmission constrained case (Fig.1a) shows more preference towards generation sites on the western part of the region where a large part of the electric load is located. The tendency towards selecting wind sites on

[4] The model only limits the power transfer between two connected regions, considering transmission flows independent on each other.

[5] Power output data are also available at http://mercator.nre.gov/wwsi.

[6] We have aggregated the 10 minute data up to hourly data to make the optimization problem manageable and to be consistent with the solar and load data which are available at only the hourly level.

[7] The model is available at http://rredc.nrel.gov/solar/calculators/PVWATTS/version1/.

[8] More exactly, the 'large scale, coarse' grid which is the result of aggregating the existing electric grid.

[9] For the transmission limited case, the coincident peak of dispatchables is 91 GW, but the assumed/required capacity is 95 GW

[10] This comes despite the fact that dispatchable generation and curtailments are strongly anti-correlated

region borders (Fig.1b)[11] is decreased by the onset of transmission constraints; in this sense the geographic site selection becomes more uniform when the electric grid is taken into consideration.

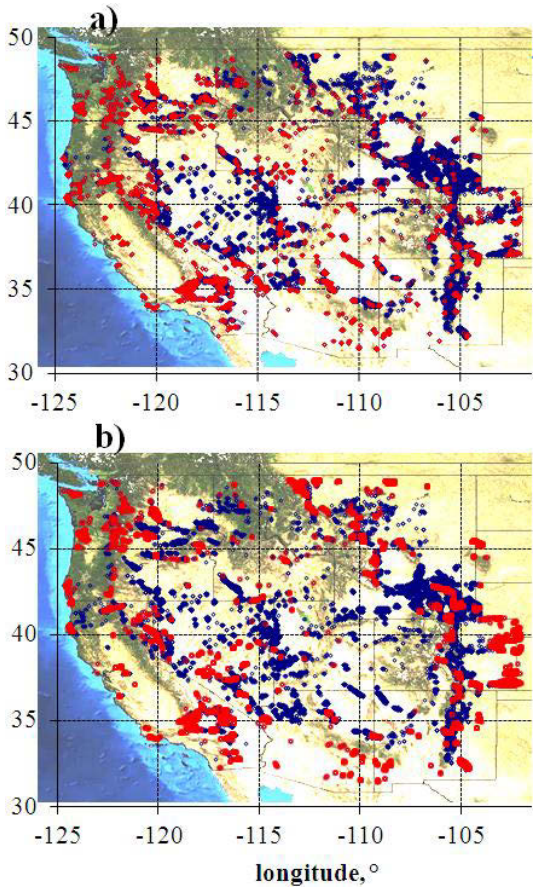

Figure 1. Optimal wind site locations with (a) and without (b) transmission limitations. Red symbols represent selected sites, blue symbols – sites that are not selected for best load matching.

CONCLUSIONS

Our results indicate that, without storage, wind and PV could meet at most about 70% of the WECC loads within the existing large scale electric grid structure. This result is qualified with the words "at most" because our analysis does not consider costs and includes only one year (*i.e.* 2005) of load and wind/PV generation data. This is therefore a practical[12] upper bound on the potential contribution of wind and PV.

[11] By choosing wind sites on region borders, correlations in their generation are minimized

[12] It is not a true upper bound as it would always be possible to add even more wind and PV if they impacted even one hour positively.

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Table 1. PV and wind contribution to energy production in Western U.S. The first (leftmost) column denotes the case modeled, the meaning of the numerical values is described in the top row; the **bold** typeface numbers denote constraints (inputs), and the <u>underlined</u> numbers represent values that are minimized (having several underlined numbers in one row means that their sum is minimized). For example, the overall dispatchables capacity is limited not to exceed 95 GW (in bold, second row). In both rows, the sum of total dispatchable generation and surplus is minimized.

case definition	wind capacity, GW	PV capacity, GW	capacity value[13], %	max surplus, GW	total surplus, TWh	total dispatchables TWh	total dispatchables % of 2005 load	max dispatchables GW
no transmission limitations	175	113	13%	100	<u>58</u>	<u>139</u>	20%	88
with transmission limitations	159	123	11%	101	<u>51</u>	<u>192</u>	28%	91, g=**95**

[13] The capacity value is calculated as the ratio of avoided conventional generation capacity (maximum load minus max dispatchables) and built renewable capacity including storage (wind plus PV capacity).