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Comparison of Solar and Wind Power Generation Impact on Net Load across a Utility Balancing Area

Matthew Lave and Abraham Ellis
Sandia National Laboratories, Livermore, CA and Albuquerque, NM, 94550 and 87185, USA

***Abstract* — As PV and wind power penetrations in utility balancing areas increase, it is important to understand how they will impact net load. We investigate daily and seasonal trends in solar power generation, wind power generation, and net load. Quantitative metrics are used to compare scenarios with no PV or wind, PV plus wind, only PV, or only wind. PV plus wind scenarios are found to have a larger reduction in maximum net load and smaller ranges between maximum and minimum load than PV only or wind only scenarios, showing that PV plus wind can be a beneficial combination.**

I. Introduction

As the installed capacity of renewable generation in utility service territories grows, it is important to understand how the variable power output can impact net load. Ideally, renewable generation would be perfectly correlated with load (as dispatchable power sources are). In practice, however, the variable power output of solar and wind generation does not perfectly match load.

To understand the value of adding wind and solar generation, it is important to understand how they match up with net load. Here, we compare wind and solar profiles to load profiles to identify trends in each and demonstrate how wind and solar can work together to complement one another.

II. Wind, Solar, and Load Profiles

The data used here was created in a previous study [1]. In that study, power output for current and future anticipated PV in New Mexico was simulated based on irradiance measurements for use in a renewable integration study. For the same renewable integration study, actual wind and load measurements in this New Mexico balancing area were also available. We use those three data sets in this analysis.

A. Solar Power

Figure 1 shows the total average total PV power as a function of hour of day and month of year. 388MW of PV, consisting of current and anticipated future utility-scale and distributed PV installations ("2023 scenario"), were simulated using irradiance measurements from the year 2013. The diurnal and seasonal solar cycles are dominant: no power is produced at night, and more power is produced earlier and later in the summer months due to the extended sunlight hours. Since most PV in this scenario is single axis tracking, power output is large during all full daylight hours (i.e., hours that do not include sunrise or sunset). The largest PV power outputs occur around noontime in April, May, and June.

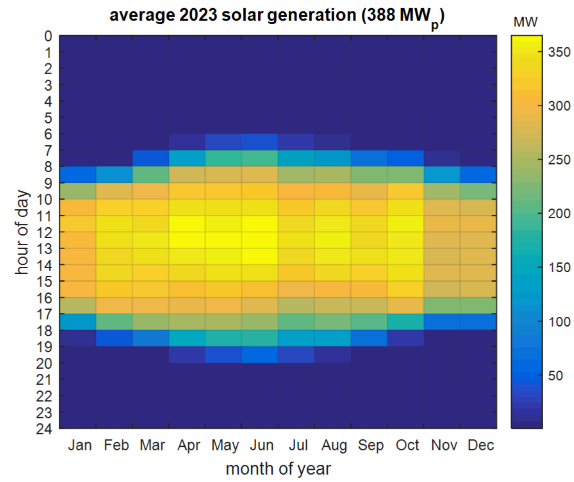


Figure 1: Average solar power output for each hour of day / month of year combination.

B. Wind Power

Measured wind power output in year 2013 from 4 wind power plants (totaling 479 MW_p) was available. Figure 2 shows the average combined wind power output as a function of hour of day and month of year. As opposed to solar power, no continuous diurnal or seasonal cycles are apparent. Instead, there are distinct areas of high or low generation. Summertime, especially midday hours (9:00-15:00) have relatively low generation. Highest wind generation occurs in winter and spring evenings and nights (November-April, 17:00-2:00). Because of these patterns, wind generation is slightly negatively correlated with solar power generation: the correlation coefficient is -0.166.

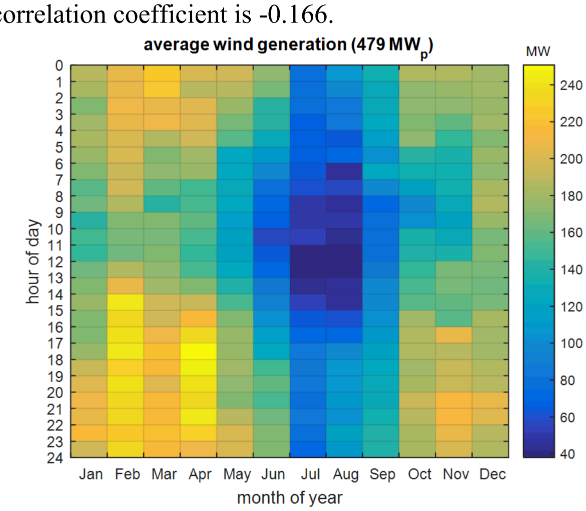


Figure 2: Average wind power output for each hour of day / month of year combination.

C. Balancing Area Load

The importance of the seasonal trends observed in solar and wind generation is in how they compare to patterns in load. Figure 3 shows the average balancing area load as a function of hour of day and month of year. Loads are highest in afternoons on summer months, and lowest in spring and fall evenings. Loads are also large during winter evenings, though not as large as summer afternoons. Solar power generation is positively correlated with load –correlation coefficient is 0.300 – since both peak in the summer daytime. Wind power generation is negatively correlated with load – correlation coefficient is -0.192 – due to the high load/low wind summertime and low load/high wind spring and fall night times.

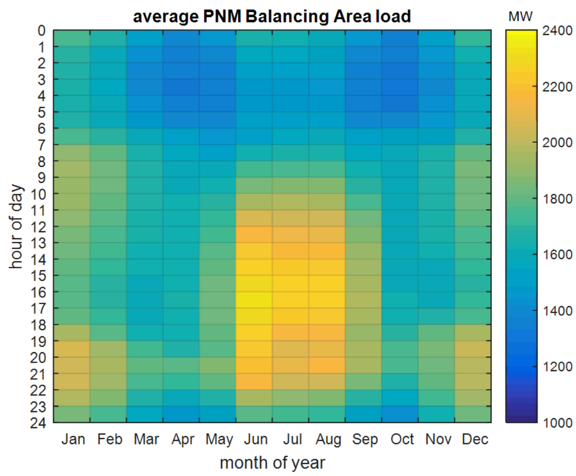


Figure 3: Average Balancing Area load for each hour of day / month of year combination.

III. Quantifying the Impact of Wind and Solar to Net Load

In this section, we use load duration curves and quantifiable metrics based on the load duration curves to quantify the impact of wind generation, solar generation, and the combination of the two on net load.

The load duration curve describes the number of hours for which each load occurs. Figure 4 shows load duration curves for load alone (no wind or solar), load minus 2023 solar, load minus wind, and load minus 2023 solar and wind.

A. Traditional Metrics

From the load duration curves, three common metrics were quantified. Although these three metrics are commonly used, their definitions vary across the literature, so a definition and citation are included for each:

- **Capacity factor:** The total energy produced by the wind, solar, or wind plus solar plants over a period of time (1-year in this case) divided by the energy that would have been produced at continuous full power output (i.e., rated capacity) during the same period [2], expressed as a percent. The capacity factor can be used to compare the value of wind and solar generation with conventional generation such as nuclear, coal, or natural gas power plants which can achieve capacity factors close to 100%.
- **Capacity value:** The average capacity factor during the 10 highest-load hours. This definition is based on the highest-load hours approximation method suggested in Madaeni, et al. [3]. This simple approximation was chosen since we did not have loss of load data for existing generation or for the future hypothetical scenarios presented. The capacity value gives an indication of the wind and solar generation's ability to displace conventional generation.
- **Peak to average demand ratio:** The ratio of peak load (or net load) to average load (or net load. [4] As the peak to average ratio rises, generators (which are procured to meet peak demand) are running on average for fewer hours or at lower power output levels, indicating lesser utilization and hence higher capital costs.

Although they have been applied to wind and solar applications, we feel the capacity value and peak load to average load metrics are not especially well suited to quantifying the impact of wind and solar generation on net load.

The capacity value as defined here shows the amount of wind or solar generation during the peak load hours. However, this does not account for the likely change in the timing of peak net load when solar generation is added (i.e., the 10 highest load hours without solar may no longer be the 10 highest net load hours with solar). Thus, the capacity value is not a true measure of the amount of capacity that can be offset.

The peak to average load ratio attempts to describe how "flat" the load duration curve is (a flatter load duration curve will mean a more consistent and hence easier to accommodate load throughout the year). However, it does not directly account for the strong reduction in minimum load that can occur when wind generation, which can be strong during low-load periods, is added. A small minimum load could impact base load choices, so is important to consider.

B. New Metrics

We propose the following two related metrics to replace capacity value and peak to average load:

- **Reduction in maximum net load (RMNL):** The average load during 10 highest load (no wind or solar generation) hours minus the average load during the10 highest net load (with wind or solar generation) hours. This value will be expressed as a percent of the added wind or solar capacity, giving units consistent with the capacity value. A value of 100% would mean that the generator is outputting power at rated capacity during peak load.

$$RMNL = \frac{\frac{\sum_{hr=1}^{hr=10} load\,(no\ wind\ or\ solar)}{10} - \frac{\sum_{hr=1}^{hr=10} net\ load\,(wind, solar)}{10}}{capacity(wind, solar)},$$

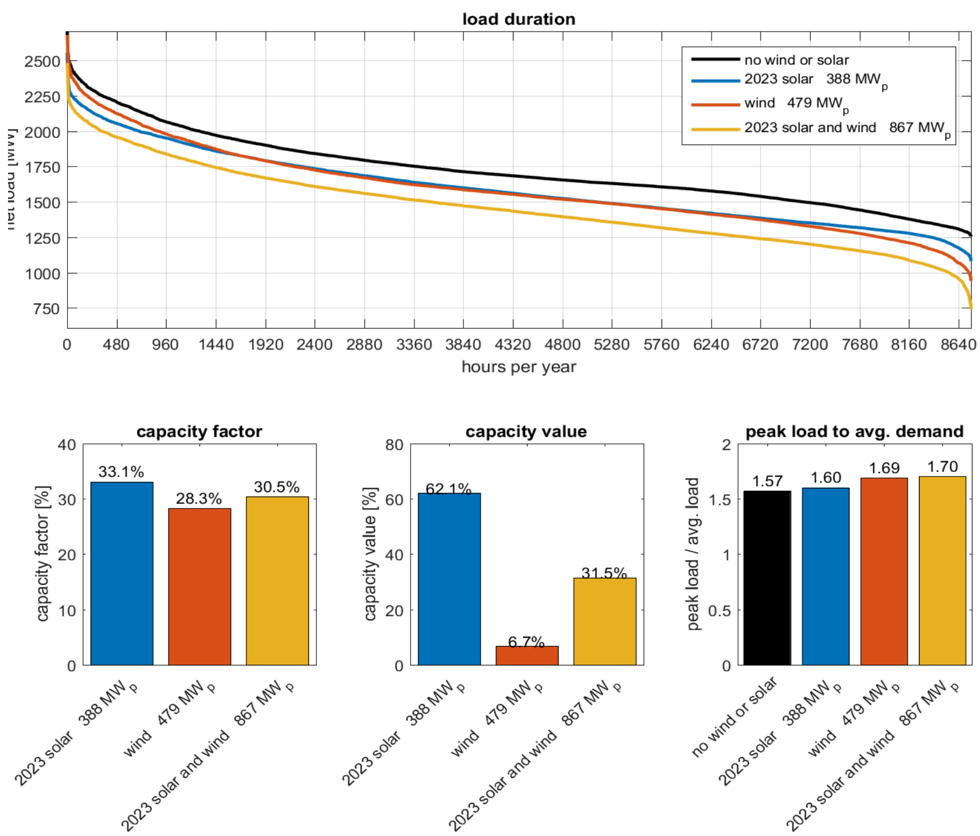


Figure 4: [Top] Load duration curves for load (black), load minus 2023 solar (blue), load minus wind (red), and load minus wind and 2023 solar (orange). [Bottom] Capacity factor, capacity value, and peak load to average load ratio.

where hr=1 is the highest load/net load hour and hr=10 is the 10th highest load/net load hour (these 10 hours may be different for load versus net load).

- **Load range change (LRC):** The difference in load range for net load compared to load with no wind or solar, normalized by the wind or solar capacity. Load range (LR) is defined as the average load during 10 highest load hours minus the average load/net load during the 10 lowest load/net load hours. The LRC is a measure of how "flat" the net load duration curve is relative to the original load. A generator that outputs constant power through the whole year would result in a LRC=0% (i.e., no change in LR). Positive values (0 to 100%) of LRC indicate an increase in LR (the addition of wind or solar decreased the minimum net load more than it decreased the maximum net load), a situation which may require more dispatchable generation.

$$LR = \frac{\sum_{hr=1}^{hr=10} load\ /net\ load}{10} - \frac{\sum_{hr=8751}^{hr=8760} load\ /\ net\ load}{10},$$

$$LRC = \frac{LR(net\ load(wind,solar)) - LR(load(no\ wind\ or\ solar))}{capacity(wind,solar)},$$

where hr=8760 is the lowest load/net load hour and hr=8751 is the 10th lowest load/net load hour (these 10 hours may be different for load versus net load).

In a rough sense, RMNL represents the amount of base load generation that can be replaced by the wind or solar and the LRC represents the added (or reduced for negative LRC values) amount of dispatchable generation required to accommodate the wind or solar. These relations would be true if load/net load had equal probabilities of occurrence at all times: at any time the maximum, minimum, or any load/net load in between could occur. In reality, loads are correlated within the same day (i.e., a high load is likely to follow a high load), and have within day and seasonal dependences (Figure 3), which allow for scheduling of certain resources and reduce the dispatchable power need. Thus, the RMNL and LRC are relevant metrics but not direct descriptors of the impact of wind or solar on generation needs. The RMNL and LRC are presented in Figure 5.

IV. Benefits of Solar Combined with Wind

We consider 3 scenarios to test how wind and solar generation impact net load: (1) solar plus load, resulting in a total of 867MW solar plus wind generation; (2) solar only, scaled (×2.2) to result in 867MW of solar generation; and (3) wind only, scaled (×1.8) to result in 867MW of wind

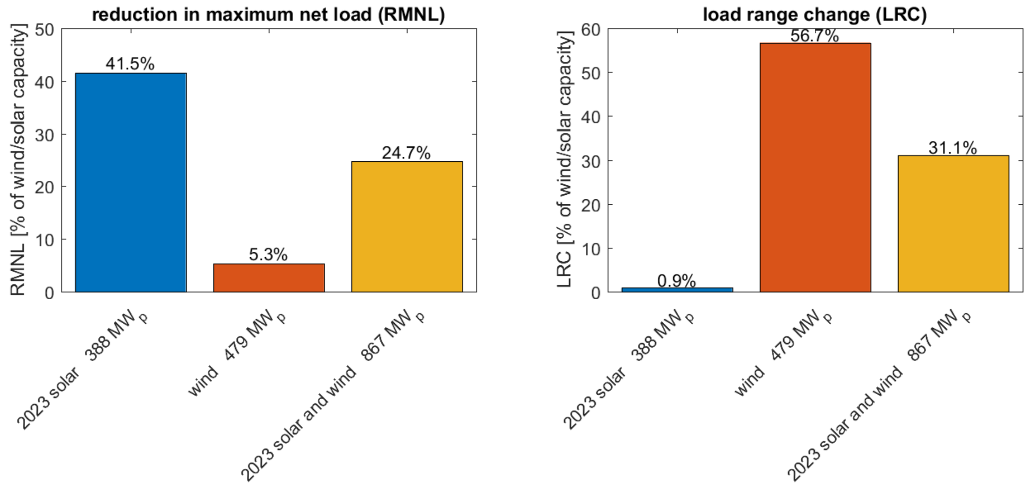


Figure 5: Reduction in maximum net load (larger is better) and load range metrics (smaller is better) for the load duration curves shown in Figure 4

generation. We note that scenarios (2) and (3) are used only for comparison and are purely hypothetical. If actual solar or wind capacities were increased significantly, it would be through new plants at new locations, likely in different weather climates.

A. Load Duration Curves

Figure 6 shows load duration curves, RMNL, and LRC for load alone (no wind or solar), and for the three 867MW scenarios.

The solar only case has a higher RMNL than the wind only case, consistent with Figure 5. However, the solar only RMNL for these 867MW (24.7%) is significantly reduced from the RMNL found for only 388MW of generation (41.5%). This is mainly caused by the timing of the net load peak: the net load peak with 388MW of solar occurred at 8PM on June 27th. Since solar generation at 8PM in June is very small (Figure **1**), the increase in solar capacity from 388MW to 867MW barely affects the net load. Increasing wind from 479MW to 867MW does further reduce the net load, resulting in a similar RMNL for both cases. However, the 867MW wind RMNL is still much lower than the solar or solar + wind RMNLs.

The LRC values for wind only are similar between the 479MW and 867MW of wind cases, but the LRC values for solar only increased significantly when the solar was increased from 388MW to 867MW. This increase is caused by a lower minimum net load value in the 867MW solar only case: during certain medium load periods, especially spring and fall mid mornings, solar generation is large enough to cause new minimum net load periods (see Figure 7). The solar plus wind 867MW case has a smaller LRC than either the solar only or wind only cases.

B. *Net Load Profiles*

Figure 7 shows hour of day / month of year plots for the net load in the each of the three scenarios. From these plots, we see that the solar only case (middle plot in Figure 7) reduces the mid-afternoon summertime load, but has no impact on the evening loads after sunset. This means that a limit is reached whereby the solar only case can no longer reduce the maximum load. When wind generation is scaled to 867 MW_p (bottom plot in Figure 7), the maximum load is only slightly reduced since wind generation is low during summer daytimes. This wind only scenario also leads to reductions at night in spring months, which decreases the minimum load and hence slightly increases the load range.

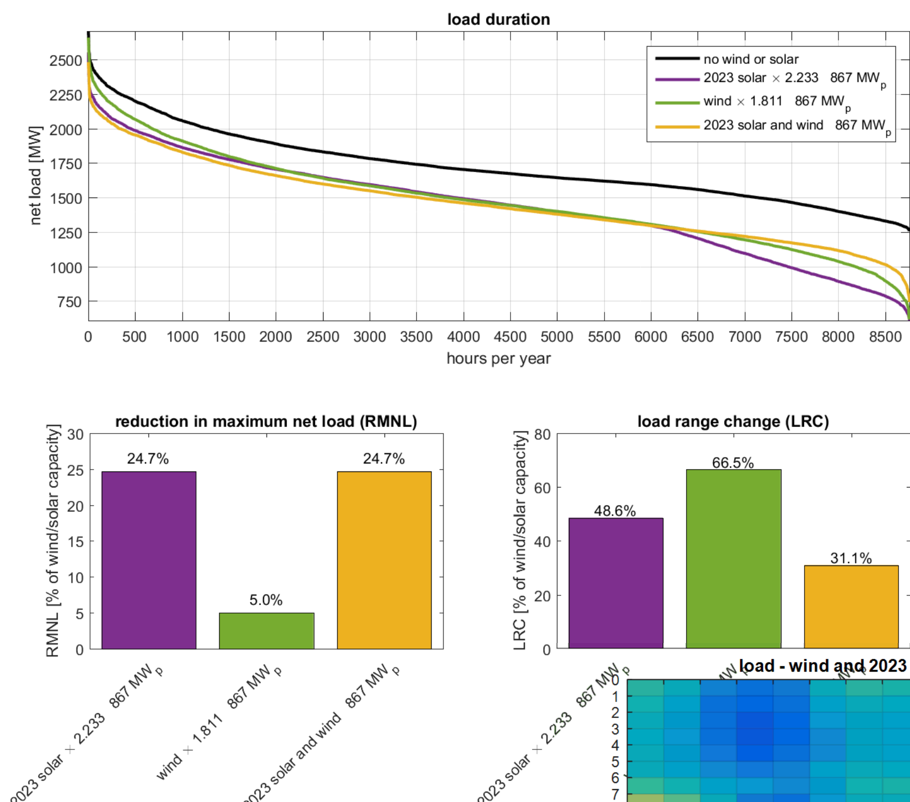
The combined wind and solar case (top plot in Figure 7) has a more even spread of net load. The solar contributions reduce the load during summer afternoons, and the wind contribution reduces the load during evenings. The maximum net load still occurs in summer evenings, but is less than in the solar only case. This again demonstrates that solar plus wind is a better case than solar alone or wind alone.

V. Optimization of Solar and Wind Combinations

In section we compared scenarios of 867MW of wind generation or solar generation to 867MW of combined wind and solar generation. The wind and solar combination was fixed: 479MW of wind and 388MW of solar. In this section, we compare various combinations of wind and solar to test the impact on net load.

Figure 8 shows RMNL and LRC values when integrating different amounts of renewable generation (y-axis) in different proportions of wind and solar (x-axis). Red lines indicated optimal values (maximum RMNL; minimum LRC). For small capacities of renewable generation (<250MW), 100% leads to the best performance. However, as capacities increase, including wind in the mix becomes more important. Combinations of roughly 50% wind and 50% solar lead to the largest RMNL and smallest LRC values when total renewable generation is around 1500MW.

Also included in Figure 8 are plots of percent energy from wind solar (relative to balancing area load), and RMNL-LRC. In all cases, 100% solar leads to the most energy produced, since solar has a higher capacity factor Figure 4 than wind. The quantity RMNL-LRC, which balances the positive benefit



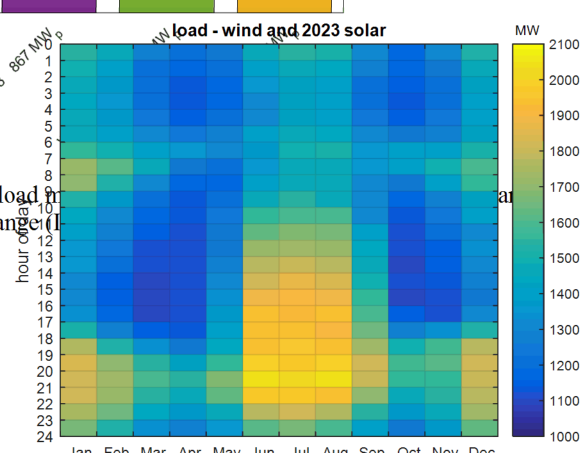


Figure 6: [Top] Load duration curves for load (black), load minus solar (blue), load m... (orange). [Bottom] reduction in maximum net load (RMNL) and load range change (L...

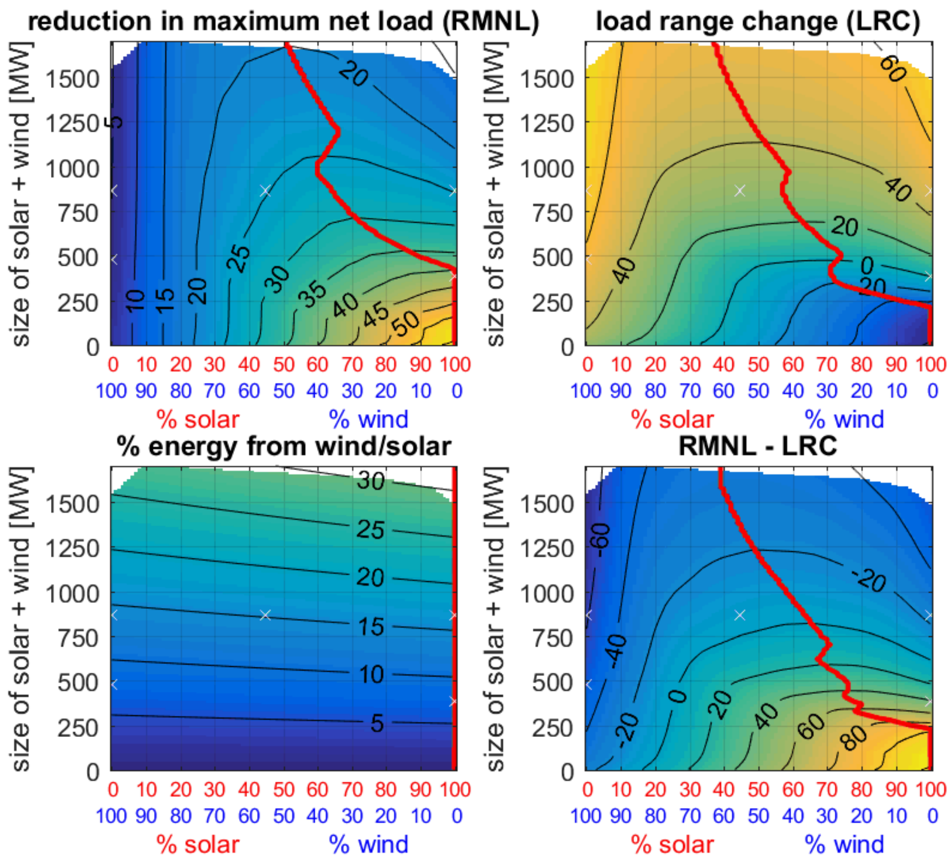


Figure 8: RMNL, LRC, % energy from wind and solar, and RMNL-LRC for varying combinations of wind and solar (x-axis) and varying combined capacities of wind and solar (y-axis). The red line in each plot shows optimal wind and solar combination (maximum RMNL, % energy, RMNL-LRC; minimum LRC) for each MW size of renewable generation. White x's in each figure indicate previously presented scenarios (in Figure 5 and Figure 6**Error! Reference source not found.**). Unresolved (white) areas indicate combinations which resulted in negative net load and so were removed from consideration.

of larger RMNL with the negative cost of higher LRC, again shows that optimal combinations at small capacities are entirely solar, but, at larger capacities it becomes important to also include wind for best benefit to load duration curves.

VI. Conclusion

Comparison of solar and wind generation to load data showed that solar was slightly correlated with load while wind was less (and negatively) correlated. While this might suggest that solar alone would have the most value in displacing conventional generation, it was seen through further analysis that solar plus wind can be a better combination than solar alone. Optimization over combinations of wind and solar showed the importance of including both wind and solar in the generation mix for large renewable generation capacities.

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