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Opportunities for Hybrid Wind and Solar PV Plants in India

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The share of variable renewable energy (VRE) on India's grid has grown significantly in recent years, and the government has ambitious plans to accelerate its growth. The country surpassed 100 GW of renewable capacity in 2021 and plans to reach 500 GW by 2030 (Gupta 2021; IndBiz 2021). Wind and solar PV are expected to play a major role in achieving this goal (Chernyakhovskiy et al. 2021; Central Electricity Authority 2020). One strategy to increase wind and solar photovoltaic (PV) deployment is through the co-location of wind and solar PV plants to form a single hybrid power plant. By building wind and solar PV in the same location, hybrid plants have the potential to reduce transmission infrastructure costs and variability in the output power profile, compared to a stand-alone plant with a single technology. This is because the times at which the two technologies generate electricity are complementary in India; in general, wind speeds tend to increase during and after sunset hours. However, questions remain regarding the potential savings from hybridizing wind and solar PV plants in India and the locations for these opportunities. This resource analysis aims to address these questions and take a first step toward quantifying the opportunities for hybrid wind and solar PV plants in India.

To identify potential locations for hybrid plants, we compared the levelized cost of energy (LCOE) of hybrid and stand-alone plants at all locations in India where VRE development could occur. As detailed in **Textbox 1**, our calculation of LCOE includes the capital cost, fixed operational and maintenance cost, and cost of interconnection. Because hybrid plants share a single interconnection, transmission costs savings may lead to a lower LCOE. For a given location, if the LCOE of a combined wind and solar PV plant is lower than the LCOE of either stand-alone technology, then a hybrid plant may provide some benefit. We find that the best locations for hybrid plants exhibit both (1) a high interconnection cost and (2) a wind capacity factor between roughly 34% and 38%. As shown in **Figure 1**, suitable locations for hybrid plants are

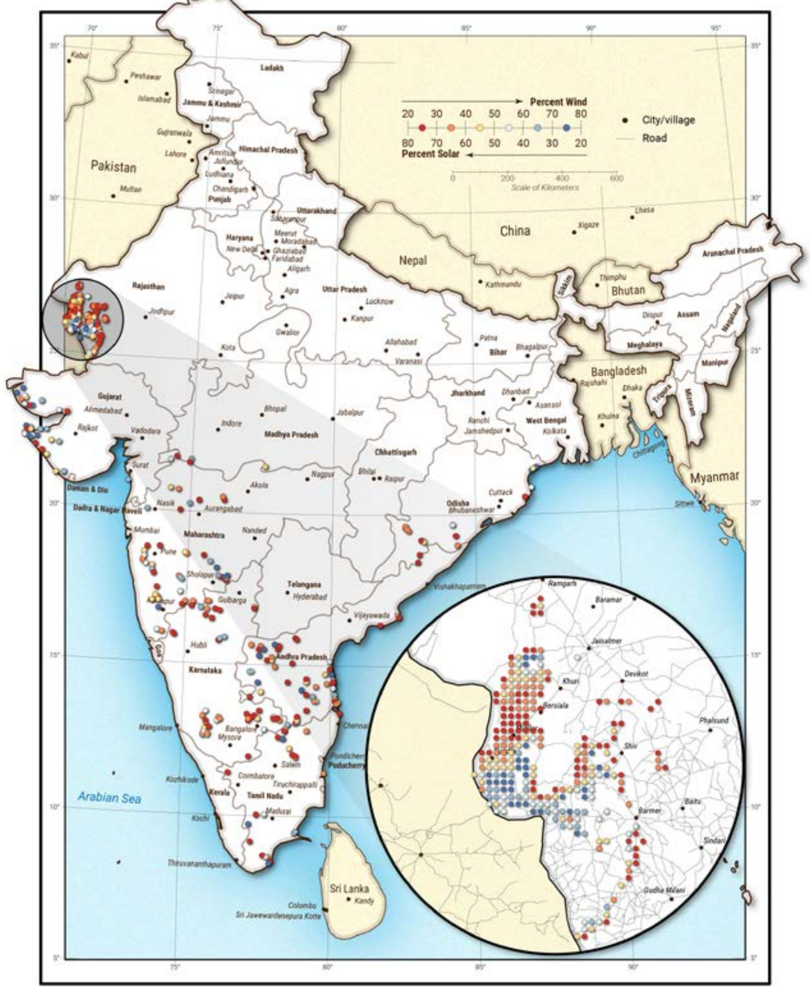

Figure 1. Estimated locations for hybrid wind and solar PV plants. Red dots indicate a higher proportion of solar PV, and blue dots indicate a higher proportion of wind. Only sites with a solar PV percentage between 20% and 80% are shown, to illustrate the criterion from MNRE's 2018 national hybrids policy. *Map by Billy Roberts, NREL.*

Textbox 1. Minimum LCOE Calculation

A relatively simple method for quantifying the energy cost of a particular VRE plant is to calculate the total cost of producing a unit of energy. This metric, known as LCOE, is shown in **Equation 1**.[a]

$$Lifetime\ LCOE\ \left(\frac{INR}{MWh}\right) = \frac{capital\ expenditure + interconnection\ cost + \sum_{t=0}^{30\ years} fixed\ operational\ \&\ maintenance\ cost_t * discount\ rate_t}{average\ annual\ capacity\ factor * 8760\ hours * \sum_{t=0}^{30\ years} discount\ rate_t}$$

We used the National Renewable Energy Laboratory's (NREL's) Renewable Energy Potential (reV) tool with high resolution solar irradiance and wind speed data from the National Solar Radiation Database and Wind Integration National Dataset Toolkit to estimate capacity factor (CF) profiles for 30 km x 30 km grid cells across India and to calculate the LCOE. The geospatial electrical network data in reV was used to calculate the cost, in lakh/MW, of interconnecting new capacity in each location given the availability of nearby transmission.[b,c] We used the following assumptions of technology costs in 2030, the year for the 450-GW renewable energy target: capital costs of 554 and 334 lakh/MW, and fixed operational and maintenance costs of 23 and 10 lakh/MW for wind and solar PV, respectively. The cost and CF assumptions were used in Equation 1 to calculate the LCOE of stand-alone wind and solar PV for each grid cell.

We used a brute force optimization across a range of hybrid plant configurations—from 100% solar to 100% wind—to identify the type of plant with the lowest LCOE for each grid cell. The CF profile for each hypothetical hybrid plant, shown in the denominator in Equation 1, was equal to the profiles of the individual resources multiplied by their respective ratios with the interconnection capacity. These ratios of generator-to-interconnection capacity were the decision variables in the optimization, and we varied them from 0 to 2. In any hour, if the power output from a hybrid configuration exceeded the interconnection capacity, we limited the output to the interconnection capacity. The configuration with the lowest LCOE was assumed to be the optimal ratio of wind and solar PV capacity in each location.

[a] Our determination of where VRE development could occur is based on a set of land exclusions, including urban, rural, and protected areas, croplands, forest, grassland, bare lands, wetlands, water bodies, and airports. For more details, see Chernyakhovskiy et al., 2021 (Table A-15).

[b] These interconnection costs are common among NREL's other long-term planning studies in India, such as Chernyakhovskiy et al., 2021 and Rose et al., 2021.

[c] One lakh is 100,000 rupees

most prevalent in western Rajasthan, western Gujarat, and a scattering of sites across southern India. The map shows the locations that, after optimizing for the mix of solar PV and wind at each site, theoretically meet the criterion from India's Ministry of New and Renewable Energy (MNRE) national 2018 policy for hybrid plants (MNRE 2018). The policy requires that the nameplate capacity of one technology is at least 25% the capacity of the other to qualify as a hybrid. In total, roughly 49 GW of wind capacity and 32 GW of solar capacity could achieve a lower LCOE in a hybrid configuration than in a stand-alone configuration at the same location. The results in Figure 1 also show the relative fractions of wind to solar PV that are optimal in each location. Red grid cells indicate sites where the lowest LCOE would be achieved with a solar-dominant hybrid plant, while blue cells represent locations favorable for wind-dominant hybrids. White cells show areas where an even proportion of wind and solar PV is optimal. Of these hybrid suitable sites, 63% are solar-dominant.

The cost-savings benefit of hybrid plants compared to stand-alone plants is relatively small, but this simple method does not capture the value of the electricity generated by looking at energy prices, nor does it quantify the potential of hybrids to provide other value streams such as firm capacity and reserves. Further, because the work does not compare solar PV and wind hybrids to alternative generation technologies or storage systems, it cannot be considered a holistic cost-benefit analysis.

Hybrid Site Optimization: Two Examples

In cases where the wind and solar resource quality are comparable or hourly resource profiles are complementary (anti-correlated), combining the two technologies can result in more annual energy, relative to investment and operating cost, compared to developing either stand-alone resource. **Figure 2** illustrates the diurnal average power output for two hypothetical hybrid plant sites with an assumed interconnection capacity of 200 MW. In the first example, on the left, the wind and solar PV nameplate capacities are similar. Even with a total installed capacity of over 300 MW, the complementary wind and solar generation profiles only exceed the 200-MW interconnection capacity during ~1% of hours, resulting in less than 1% clipped energy. Energy

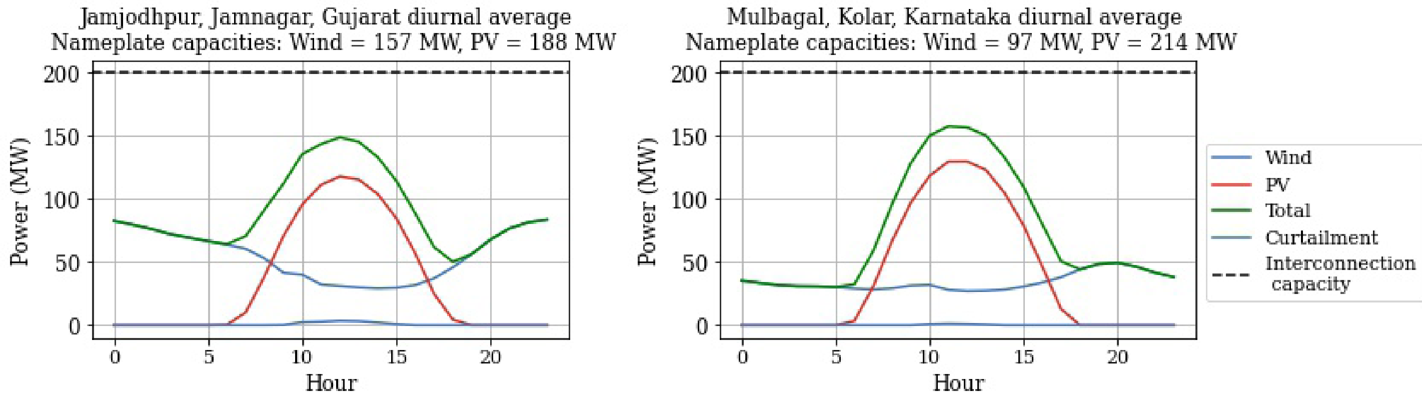

Figure 2. Diurnal average power output curves for two hypothetical LCOE-optimized hybrid plants

clipping, also known as curtailment, happens when the output from the VRE power plant exceeds the interconnection capacity, and the excess cannot be injected into the grid. Because the LCOE optimization chooses the ideal generator-to-interconnection ratio, less than 1% of the annual energy is curtailed at all sites across India.

The second example, on the right, illustrates a site where a solar-dominant location would benefit from adding a small amount of wind. The additional wind reduces the LCOE of the plant by 1% compared to building a stand-alone solar PV plant. This results in energy clipping during 5% of hours, but the curtailed energy is still less than 1% of the annual total.[1]

Impact of Interconnection Costs

The economic benefit of hybrid wind and solar PV plants comes largely from avoiding new substation and spur line investments in areas where the two technologies can maximize the use of the same network infrastructure. Therefore, the estimated cost of interconnection can have a large impact on the potential locations for hybrid plants.[2]

To better understand this impact, we calculated the suitable locations for hybrid plants under a variety of interconnection cost assumptions. **Figure 3** shows the change in results across India when the assumed interconnection costs at each site are doubled. The number of suitable hybrid sites almost triples, and the total nationwide hybrid potential increases from 49 to 87 GW wind and from 32 to 99 GW solar PV.

Interconnection costs can also impact the optimal mix of wind and solar PV at hybrid locations. **Figure 4** shows the optimal hybrid plant configuration for a hypothetical site in western Rajasthan across a range of interconnection costs. When the interconnection cost is zero, an all-wind or all-solar PV plant always has a lower LCOE than a hybrid plant. This is because we only quantify cost savings from sharing an interconnection and ignore the other potential cost savings from values streams like firm capacity and reserves.

As the interconnection cost increases, it becomes less expensive to build a hybrid plant, because the energy generation profiles are complementary and more electricity can be generated without exceeding the interconnection limit. At this particular site, this economic threshold occurs above an interconnection cost of about 75 lakh/MW.

The default assumption for this site, marked by the green dotted line, is 84 lakh/MW. At this interconnection cost, our

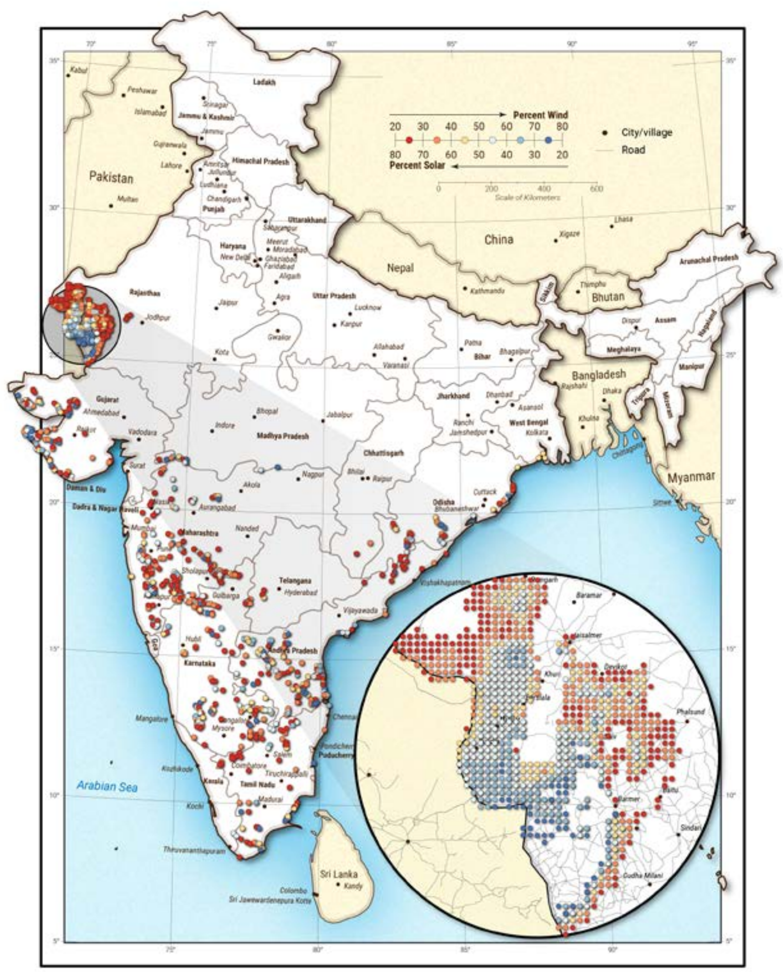

Figure 3. Estimated locations for LCOE-optimized sites, with the interconnection cost doubled from the original assumption. *Map by Billy Roberts, NREL.*

[1] Dynamic line ratings have been proposed as a method to decrease curtailment by temporarily allowing more power to flow from the hybrid plant to the grid (IRENA 2020), but that analysis is beyond the scope of this study.

[2] Interconnection costs do not capture contractual fees and tariffs.

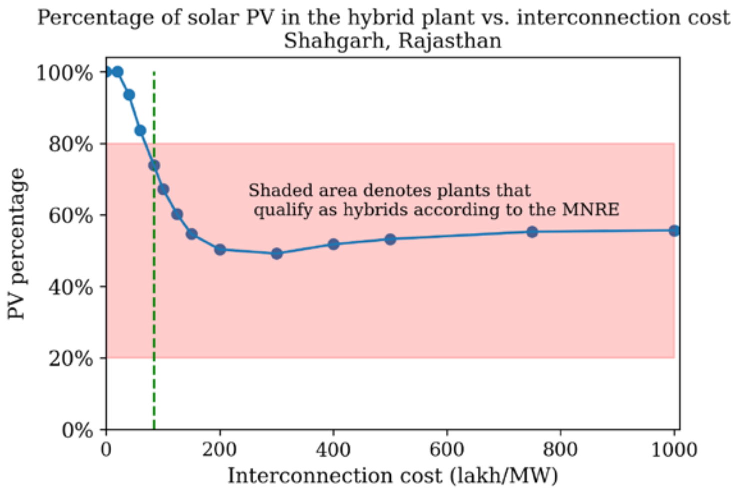

Figure 4. Impact of interconnection cost on the optimal wind/solar PV ratio for a hypothetical hybrid site in Rajasthan. The default interconnection cost assumption for this site in our analysis, marked by the green dotted line, is 84 lakh/MW. The shaded area denotes plants that qualify as hybrids according to the MNRE.

optimization found a hypothetical hybrid plant with a capacity split of 74% solar PV and 24% wind to minimize lifetime LCOE.

As the hypothetical interconnection cost increases above 125 lakh/MW, the lowest LCOE plant configuration becomes one with a more even split between wind and solar PV (between 50% and 60% PV percentage).

Increased interconnection costs also affect the design of stand-alone plants. With high interconnection costs, it becomes efficient to use the spur line at its full capacity as often as possible. This means it may be more cost-effective to oversize the generation capacity, even if it results in some energy clipping. In general, though, a hybrid plant with complementary wind and solar PV generation profiles will result in less clipping for the same level of overbuilt generation capacity compared to a standalone wind or solar PV plant.

Impact of Wind Resource

The second major factor that impacts whether a site may be financially suitable for hybrids in India is the strength of the wind resource. **Figure 5** plots the impact of the wind capacity factor (CF) on the technology mix of each hypothetical hybrid site. The CF on the x-axis represents the average strength of the wind resource at each site. The colors of the dots indicate the technology mix.

Below an average wind CF of around 32%, stand-alone solar PV plants are the lowest LCOE option for most sites. This is because the projected capital cost of solar PV in 2030 is lower than that of wind. If the wind resource is not significantly stronger than the solar PV resource at a given site, a stand-alone solar PV site will always result in the plant configuration with the lowest LCOE.

However, as the wind CF increases above 32%, it is cost-effective to add wind capacity to stand-alone solar PV plants, resulting in solar PV-dominant hybrid plants. Most (82%) of the theoretical plants that qualify as hybrids according to the MNRE's 2018 policy occur between a stand-alone wind CF of 34% and 38%. Above a wind CF of 39%, which represents 14% of all sites, mostly stand-alone wind plants achieve the lowest LCOE.

Future Work

This analysis is an initial step toward quantifying the opportunities for wind-solar PV hybrid plants in India's future energy mix. Future work can expand both the scope and scale of this analysis. For example, this analysis only considered greenfield projects and did not consider opportunities to hybridize any of the existing 44 GW of wind and 40 GW of solar PV plants already commissioned across the country. Existing stand-alone wind plants may be able to fit solar PV panels in the gaps surrounding wind turbines, presenting

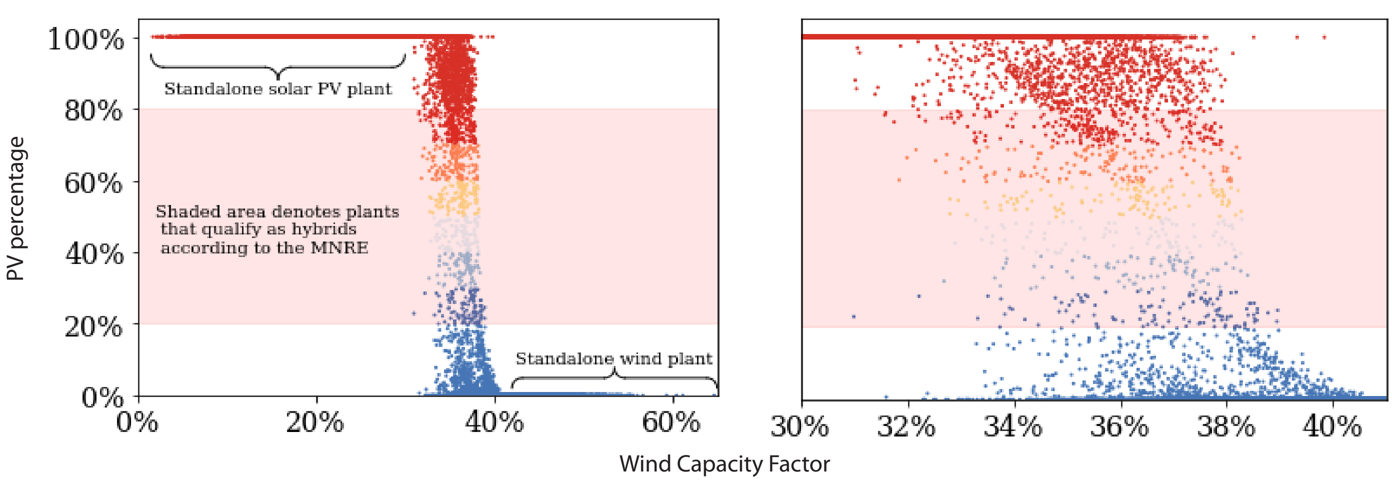

Figure 5. Impact of optimal wind capacity factor on the PV percentage in the LCOE-optimized plant, for the full range across all sites (left) and zoomed in on hybrid sites only (right). The colors represent the same PV percentage bins from Figures 1 and 3. The shaded red area denotes plants that qualify as hybrids, according to the MNRE.

an opportunity to save money on land purchasing costs. However, wind turbines generally cannot fit into the footprint of existing solar PV plants.

Further, this study does not consider hybrid plants that utilize energy storage systems. Storage can improve the capacity credit and reliability of the hybrid plant as well as allow for more custom plant configurations to maximize the value of a hybrid plant. Storage can also potentially unlock additional ancillary service value streams, to which stand-alone VRE plants usually cannot contribute. Future analysis could run a similar LCOE optimization but could include existing locations for wind and solar PV plants as well as energy storage technologies.

This work only evaluates a few key aspects of hybrid plants: namely, the interconnection capital cost and the ideal wind-to-solar PV ratio. This simplified approach allows simultaneous evaluation of all sites across India, but more detail would be needed to design individual plants. Developers can utilize tools such as NREL's open-source Hybrid Optimization and Performance Platform to optimize the individual components of their hybrid plants, as well as run a detailed financial analysis (Dykes et al. 2020).[3]

Hybrid power plants could offer other benefits beyond lower LCOE. Future work can investigate the impact of hybridization on a plant's contribution to resource adequacy, ramping needs, and other ancillary services. These services will become increasingly important as VRE contribution in the electricity generation mix increases. Quantifying these grid benefits would require evaluation of time-synchronous plant output and system-wide electricity load, for example, in a production cost model.

As India looks increasingly to VRE to meet its electricity needs, wind and solar PV hybrids have the potential to provide lower energy costs compared to stand-alone technologies in specific locations. Technical assessments such as these can inform policymakers, regulators, electric utilities, and project developers as they seek to identify the role for hybrid plants in India's electricity mix.

[3] https://www.nrel.gov/wind/hybrid-energy-systems-research.html.

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