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Feasibility and Impact of Biomass and Renewable Energy Hybrid Systems

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FEASIBILITY AND IMPACT OF BIOMASS AND RENEWABLE ENERGY HYBRID SYSTEMS

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List of Acronyms

CEA	Central Electricity Authority, Ministry of Power, Government of India
CEEW	Council on Energy, Environment, and Water
CERC	Central Electricity Regulation Commission
INR	Indian Rupee
kWh	Kilowatt Hour
GW	Gigawatts
GWh	Gigawatt hours
LBNL	Lawrence Berkeley National Laboratory
LCOE	Levelized Cost of Energy
LNG	Liquefied Natural Gas
MW	Megawatts
NIBE	National Institute of Bio-Energy (India)
O&M	Operations and Maintenance
MT	Metric Tons
PLF	Plant Load Factor
RE	Renewable Energy

1 Background

India has set ambitious clean energy targets for the power sector, namely 175 GW of renewable energy (RE) installed capacity by 2022 and 500 GW of installed RE capacity by 2030. India has made rapid progress toward achieving these goals. Between 2015 and 2021, it more than doubled its RE capacity from 40 GW to 100 GW, supplying nearly 10% of the total electricity generated in the fiscal year 2021 (CEA 2021). Moreover, over the last decade, India has successfully achieved some of the lowest RE costs in the world. Between 2010 and 2020, it reduced the levelized cost of energy (LCOE)[1] for solar by 85%, the largest reduction of any country, while the average solar tariff in 2020 was 34% lower than the global weighted average. Compared with other countries, India had the lowest installed cost for solar and wind in 2020, as a result of competitive bidding for grid-scale RE plants (Gadre, Jain, and Shantanu 2020) (see Figure 1).

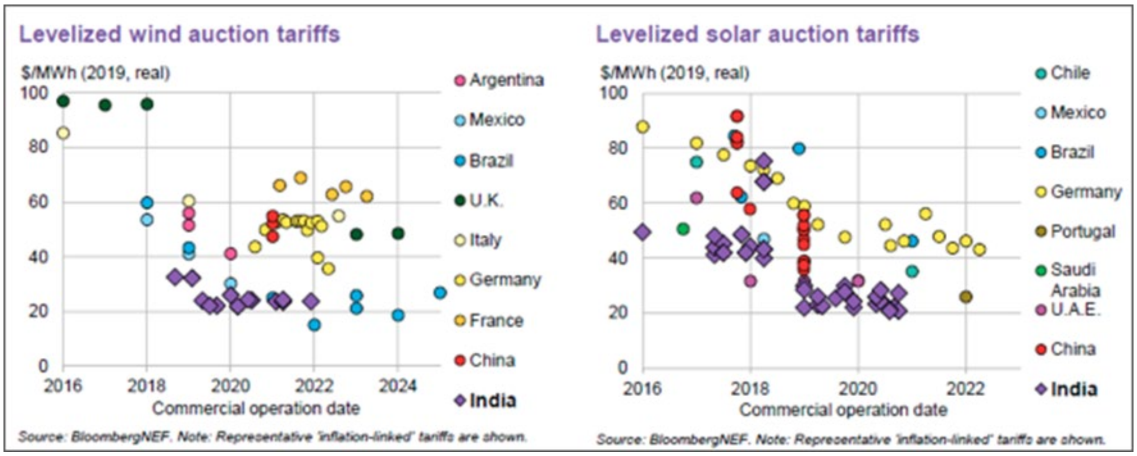

Figure 1. Solar and wind energy prices in key countries, including India

(Figure source: Gadre, Jain, and Shantanu 2020)

It is widely accepted that renewable electricity costs have dropped below thermal generation costs on a levelized basis. Nonetheless, planned investments in new fossil fuel power plants continue primarily because

- RE generation is intermittent and may need significant system flexibility for grid integration,
- RE generation does not coincide with peak electricity demand periods (which is in the evening for most parts of India), and
- legacy planning and regulatory frameworks may not fully capture the value and capabilities of RE and energy storage technologies.

In this context, the dramatic decline in battery storage costs — 90% cost reduction at the battery pack level since 2010 — could serve as a tipping point because it enables the cost-effective supply of low-cost renewable electricity during peak times (see Figure 2). Using market trends from the United States and bottom-up estimates, Lawrence Berkeley National Laboratory (LBNL) projected Lithium-ion battery prices (as levelized cost of storage) for India for grid-scale applications (Deorah, Abhyankar, Arora, Gambhir, & Phadke, 2020). This report estimated that, by 2030, the additional cost of adding battery storage equivalent to 30% of daily solar generation would be about INR 1/kWh.[2] Therefore, the cost of power from a solar-plus-storage plant that could extend solar

[1] LCOE refers to the estimates of the revenue required to build and operate a generator over a specified cost recovery period (U.S EIA [2021]).

[2] Termed as the "storage tariff adder," this is the cost of storage spread out over all solar generation.

generation to evening peak hours would be about INR 2.5/kWh (assuming the solar price to be INR 1.5/kWh by 2030), which is greater than variable cost of 100 GW of installed coal capacity.

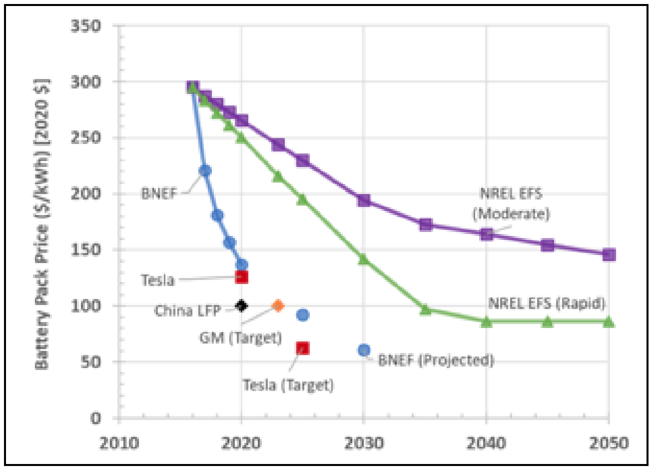

Figure 2. Global average battery pack prices since 2015 till 2050

(Data source: BNEF 2020)

Overall, as India's grid attains higher penetrations of renewables, the task will be to balance its variability through a spectrum of flexible resources that work in tandem to maintain the hourly supply demand.

In a separate report, LBNL assessed a least-cost optimal mix of resources to meet India's projected demand in 2030 (Abhyankar, Deorah, and Phadke 2021), henceforth called the ***"2030 India Report."*** 307 GW of solar and 142 GW of wind was found to be cost-effective along with a range of flexible resources such as 63 GW of energy storage, 60 GW of load shifting from nighttime to solar hours and using the existing gas-based capacity for seasonal balancing during low RE season (October through February). Figure 3 shows the 2030 projected load and net load assuming this least cost resource mix (450 GW of solar plus wind capacity).

Increasing solar generation during daytime hours results in significant ramping requirements on the 2030 Indian grid compared to the 2020 grid. Specifically, the difference between the daily load and net load[3] for key months of the year dramatically increases between 2020 and 2030, resulting in the steep ramps during morning and evening peak times in 2030 (see Figure 3).

[3] Net load (or residual load) is defined as load minus the output from variable RE sources (solar and wind).

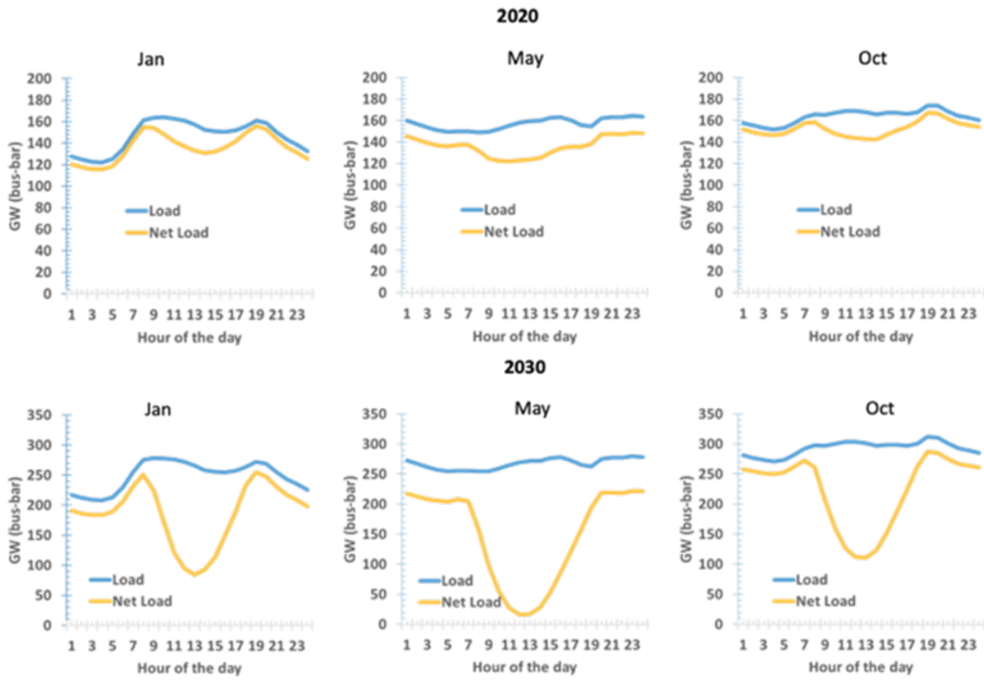

Figure 3. Average daily load and net load curve for key months in 2020 and 2030

(Figure source: Abhyankar, Deorah, and Phadke 2021)

Under such a scenario, flexible resources such as energy storage, demand response (agricultural load shifting), and flexible operation of gas and biomass power plants would become increasingly important for ensuring affordable, stable and reliable grid power. During the high RE generation season (June through September for wind and March through June for solar), flexible sources will be required to provide diurnal grid balancing to meet steep system ramps (see Figure 4).

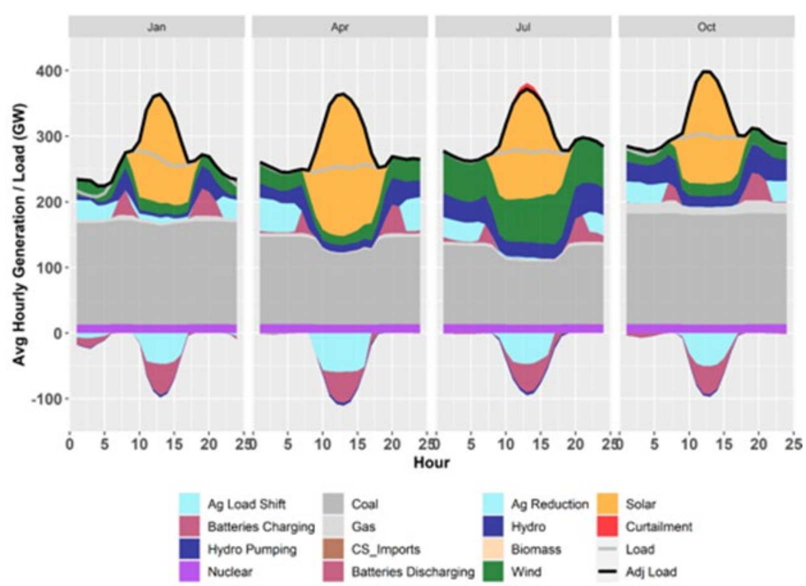

Figure 4. Average hourly dispatch for key months in 2030

(Abhyankar, Deorah, and Phadke 2021)

During the low RE generation season (October through February), there is not enough RE generation to charge batteries using solar or wind power. Therefore, flexible generation resources like natural gas and biomass generation (in lieu of coal-fired assets) will play a crucial role in providing seasonal balancing with most of their dispatch occurring during these months (see Figure 4).

Within this broader context and building on existing work, this study aims to assess the techno-economic potential of biomass and hybrid biomass-RE systems for India's evolving grid by considering the biomass supply chain, fuel availability, and technical operation constraints. It estimates the potential value of biomass-based power plants to the Indian grid in 2030, with high RE penetration, and evaluates the capability of biomass-based power plants to provide the necessary grid balancing services that would be required (both diurnal and seasonal). The insights from our analysis could inform policymakers on the role biomass systems could play in India's power sector going forward.

2 Biomass Scenario in India

India has two planting and harvesting seasons relevant to biomass-based energy generation. Seeds for the Rabi season are generally planted between October and December and harvested between April and June. Rabi crops include rice, maize, wheat, sugarcane, and cotton. Kharif crops, considered the second season of the year, are typically sown early in the Indian Monsoon and harvested between September and October. Kharif crops include rice, maize, wheat, sugarcane, mustard, and potato. According to National Institute of Bioenergy (NIBE) data, the states with the highest installed biomass capacity are Uttar Pradesh, Maharashtra, and Karnataka.

In 2020, India's installed biomass-based generation capacity was approximately 10 GW, of which 75% was sugarcane bagasse-based cogeneration (CEA-CEEW 2021). Since these cogeneration plants primarily produce sugar during the Kharif season, with electricity as a by-product, actual generation from bagasse power plants is concentrated between October and May (see Figure 5). Bagasse availability and generation are thus highly seasonal, with an average plant load factor (PLF) or capacity factor of 26% between November and May, and low-capacity factors of 4% the rest of the year. Additionally, reported PLF is for power exported to the grid, though actual PLF might be higher.

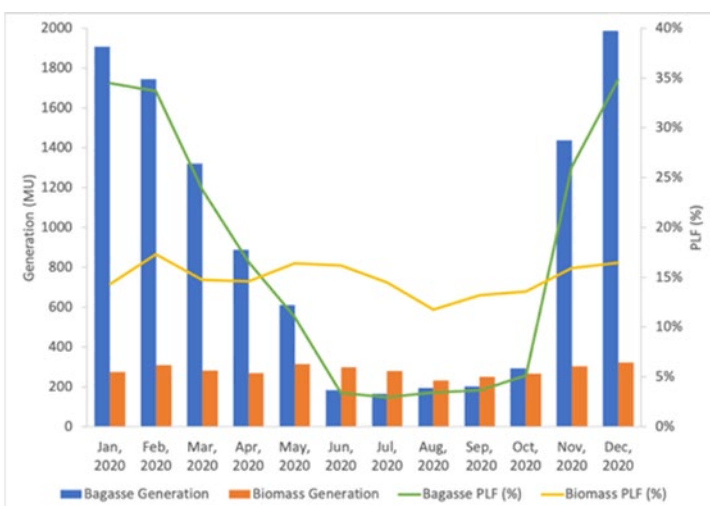

Figure 5. Monthly bagasse and biomass generation and Plant Load Factors (PLF) for 2020

(Data source: CEA-CEEW 2021)

This seasonality contrasts with other biomass-based generation, mainly from rice husk and bio-waste from other pulses produced all year, thus maintaining a flat generation profile with a PLF of ~15The seasonal ramping up of bagasse cogeneration in November aligns very well with the seasonal balancing requirements of the Indian grid envisaged for 2030.

According to the Central Electricity Authority (CEA), India's current biomass-based installed generation capacity is 10 GW, including 3 GW for biomass and 7 GW of bagasse-based cogeneration (CEA-CEEW 2021). Based on NIBE assessments, we conclude that total biomass power potential in India is around 30-35 GW (ASCI, 2021). This implies an additional untapped biomass-based power potential of 20-25 GW.

3 Methodology and Data

To assess the potential and value of biomass-based power plants and hybrid systems that combine them with RE in India's power sector today and in 2030, the study focused on the following key aspects:

- The value of biomass and RE + biomass hybrid systems to the grid,
- The capability of biomass plants to provide specific grid services (diurnal and seasonal balancing) while considering the economic and operational constraints of biomass-based electricity generation systems.

3.1 Biomass Value Estimation

The value of biomass and RE + biomass hybrid systems to the grid is the sum of its estimated capacity and energy value. The capacity value of a resource is equivalent to the fixed cost of the marginal unit of generation capacity that it would replace or avoid. It is typically expressed in INR/kW/year or INR/kWh for every unit of generation. The energy value of a resource is the variable cost of the marginal unit of generation it would replace.

First, we developed a monthly feedstock supply curve for the top two feedstocks based on seasonal feedstock availability data as provided by NIBE (see Table 2) (ASCI, 2021). We added a monthly supply curve for sugarcane/bagasse since 75% of the existing biomass-based generation capacity is sugarcane/bagasse based.

Table 1. Excess Seasonal Feedstock Availability in Metric Tons

Season	Rice	Maize	Wheat	Sugarcane	Cotton	Mustard	Potato
Kharif Season (June to Oct)	39.35	13.7	5.98	5.29	48.76		
Rabi Season (November to April)	16.93	6.54	22.23	2.69		3.17	12.07

(Data source: (ASCI, 2021)

As shown in Table 2, rice, and cotton are the top two feedstocks by availability. In addition to these, we considered sugarcane/bagasse as well since it accounts for almost 75% of existing biomass-based generation capacity. We translated these supply profiles into an hourly supply profile for an entire year and created a weighted biomass feedstock availability profile for the whole year[4]. This composite biomass supply profile was one of the inputs to estimate the capacity and energy value.

Another input was cost estimates for all critical generation resources on the Indian grid using data from the Central Electricity Regulatory Commission (CERC, 2020), CEA (CEA, 2021) and LBNL's 2030 India Report (Abhyankar, Deorah, and Phadke 2021). Since capital cost and O&M cost data were not available for individual feedstocks, composite supply profiles and biomass technology level costs were used to develop cost estimates. Table 2 summarizes this data.

[4] Utilizing the feedstock as per the supply profile might require added investment in feedstock storage infrastructure, which is beyond the scope of our analysis,

Table 2. Input Parameters for Capacity Value and Energy Value Calculations

	Capital Cost (INR/MW)	O&M Cost (INR/MW/year)	Variable Cost (INR/kWh)
Solar	45,000,000	375,000	
Wind	70,875,000	750,000	
Biomass[5]	60,550,000	4,642,000	5.3
Bagasse	49,200,000	2,452,000	3.9
Coal	78,500,000	1,875,000	3
Natural Gas	60,000,000	1,125,000	
Existing Liquefied Natural Gas (LNG)			3.7
Existing Domestic Gas			2.6

(Sources: CEA, CERC, LBNL)

Finally, we used data from LBNL's 2030 India Report was to derive hourly load profiles for 2030 (Abhyankar, Deorah, and Phadke 2021).

Estimating capacity and energy value required two steps. First, the capacity value of biomass (without hybridization with RE) was estimated by modeling how much biomass generation capacity could effectively replace the marginal capacity expansion unit on the grid, assumed to be a new coal-based power plant. Second, we estimated the energy value of biomass by assessing the variable cost of the marginal unit being dispatched, conservatively assumed to be constant at INR 3/kWh[6].

LBNL's 2030 India Report concluded that the least-cost pathway for India to meet the load in 2030 would consist primarily of a combination of RE and flexible resources as follows:

- 465 GW of RE (307 GW solar, 142 GW wind, and 15 GW other RE),
- 63 GW (252 GWh) of battery storage,
- 60 GW of load shifting to solar hours (50 GW agricultural + 10 GW industrial), and
- flexible operation of the existing natural gas fleet of 25 GW.

Further, a coal power plant capacity of 229 GW (23 GW net addition over 2020) was found to be cost-effective (Abhyankar, Deorah, and Phadke 2021). This resource mix supports recent RE goals announced by Prime Minister Modi in Glasgow in November 2021.

Hence, for modeling purposes, we assume that 310 GW of solar generation capacity and 140 GW of wind generation capacity will be operational in 2030. We model different scenarios of operational biomass capacity up to 30 GW in 2030. To estimate the capacity value of the RE-plus- biomass hybrid system, we modeled the total new generation capacity of coal that the hybrid system could potentially replace without any loss in generation.

The current study applied conclusions from the LBNL's 2030 India Report and models the potential value that biomass could provide to this RE-dominant portfolio. The results section shows that that biomass improves the portfolio's overall value

[5] Capital and O&M costs for plants operating on paddy residue are high due to imported equipment. Indigenization might help reduce costs.
[6] As per the 2030 India Report, 80 GW of India's coal capacity has a variable cost of over INR 3/kWh, while 40 GW has variable cost higher than INR 3.5/kWh

4 Results

4.1 Capacity and Energy Value

If by 2030, there is no additional biomass generation, the existing 10 GW of biomass generation will provide the same reliability as 8 GW of coal capacity. In terms of capacity, that value is INR 3.4/kWh or INR 8,221/KW/year. Similarly, if significant biomass capacity is added, 30 GW of biomass generation capacity can provide the same reliability as 19 GW of coal generation capacity. This is equivalent to a capacity value of INR 2.97 /kWh or INR 7,438 /KW/year. Figure 6 shows the capacity and energy value of biomass to the grid in 2030 in INR/kWh for different scenarios of installed biomass capacity.

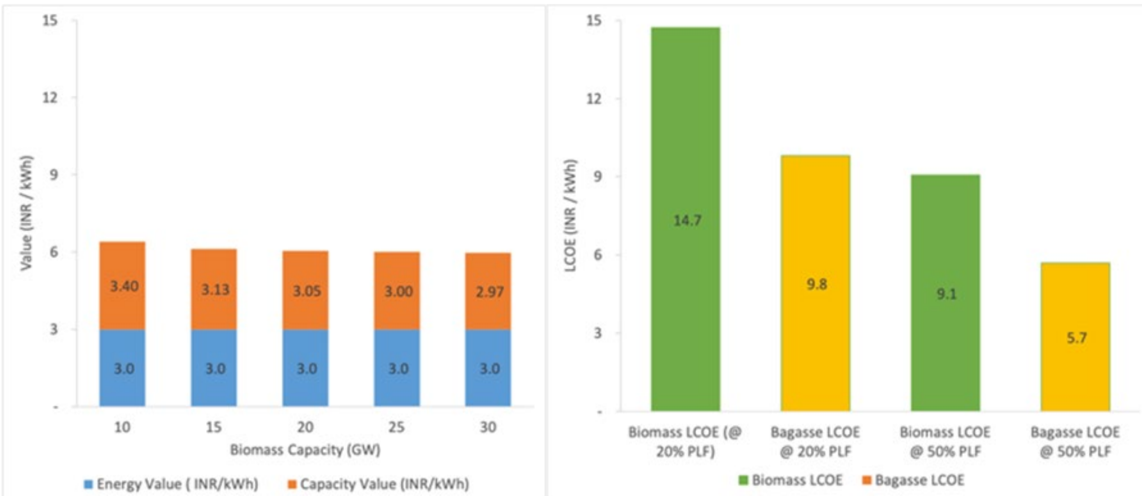

Figure 6. Capacity and energy value for different biomass installed capacities in 2030 (left) and LCOE of biomass and bagasse at current PLF of 20% and 50% in 2030 (right)

Adding new generation capacity is economically prudent when the value provided to the grid is greater than its levelized cost of energy (LCOE). As Figure 6 shows, at 10 GW of installed capacity, the total value of biomass to the system is INR 6.4 /kWh, which is lower than its LCOE at the current PLF of ~20%. Also, as the biomass installed capacity increases, the total value of biomass to the grid decreases. Therefore, at 30 GW of installed capacity, the total value is INR 5.97 /kWh. If bagasse power plants operated at 50% PLF, the LCOE would be just below the total value.

Importantly, this economic framework does not account for additional benefits of biomass-based power plants such as waste management and reduced pollution/emissions from avoided waste burning. If those value streams are included in the value estimation, the value of biomass-based plants is likely to be higher. Additionally, if natural gas was the marginal unit instead of coal, the capacity and energy value of biomass would be higher since the fixed and variable costs of natural gas power plants are higher. Finally, we assume the variable cost of the marginal coal unit to be constant for this exercise, though some older units have variable costs higher than INR 3/kWh.

In 2030, with 450 GW of solar and wind installed capacity, the capacity value of this renewable energy mix would be small. However, assuming system-level hybridization for maximizing grid value, biomass-based power plants would enhance the capacity value of the combined RE portfolio (see Figure 7).

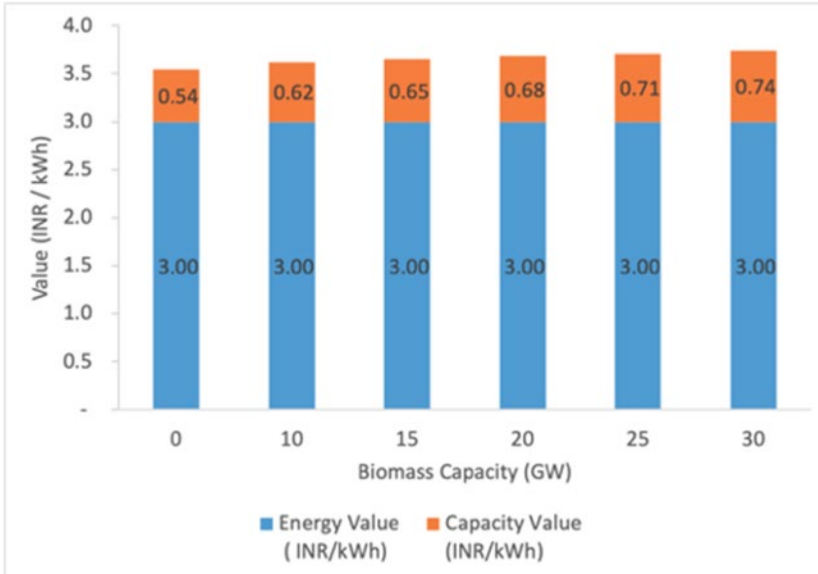

Figure 7. Adding biomass generation to the RE resource mix increases the value of the overall RE portfolio

4.2 Diurnal and Seasonal Balancing

4.2.1 Diurnal Balancing

Diurnal balancing support requires 4-6 hours of support during morning and evening peak periods for more than 300 days of the year (see left chart of Figure 8 left). Biomass is one of the resources that could provide that support, along with battery storage and coal at low-capacity factors. The right chart of Figure 8 compares the levelized cost of different resource types. Battery storage is expected to be the cheapest solution for providing diurnal balancing by 2030.

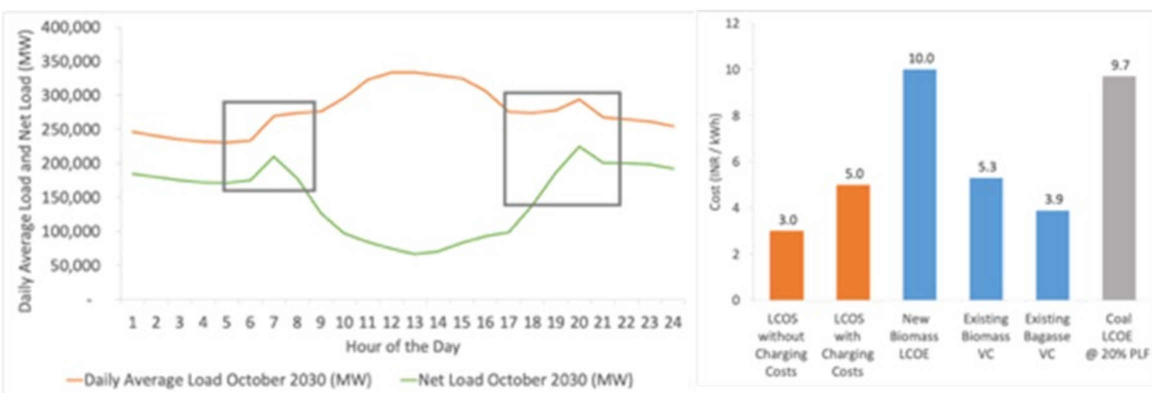

Figure 8. The average daily load and net load curve showing the morning and evening peaks when diurnal balancing support is required (left). The comparison between the costs of different resources capable of providing that support (battery storage, new and existing biomass and coal) (right).

However, biomass-based generation could have constraints in providing diurnal balancing support to the grid. Biomass combustion plants are not flexible for ramping up and down. Existing biomass capacity is predominantly bagasse-based and given that grid-connected power generation is not their primary function, operational constraints could prevent it from providing the required consistent support. From an economic perspective, existing bagasse-based generation would be cost-competitive with alternatives like battery storage, but biomass-based generation could be expensive (see Figure 8).

4.2.2 Seasonal Balancing

Seasonal balancing requires high-capacity factors of 60%-80% between October and February when RE generation is reduced (see Figure 9). Natural gas, biomass, and coal are options for providing seasonal balancing support to the grid.

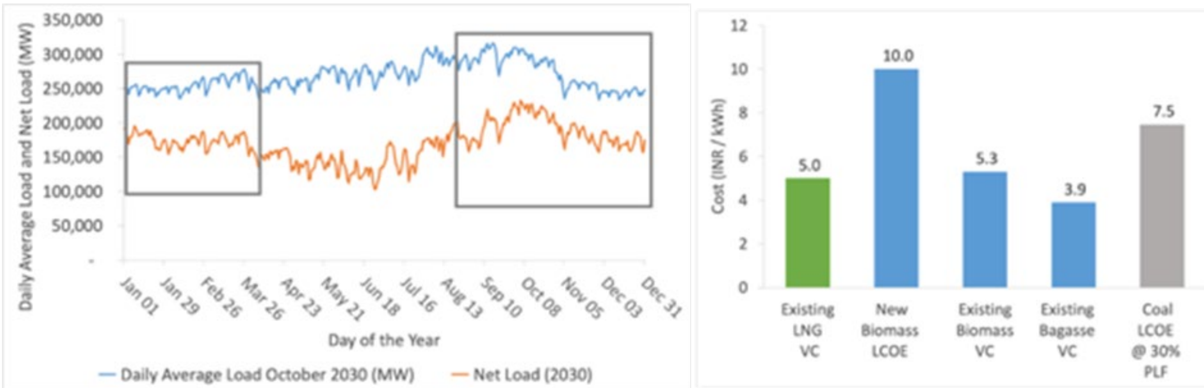

Figure 9. The average daily load and net load curve over the year when seasonal balancing support is required (left). The comparison between costs of different resources capable of providing that support such as LNG, biomass and coal at 30% PLF (right).

5 Conclusion and Recommendations

The Indian power system would need significant diurnal and seasonal balancing support from flexible generation resources with increasing RE penetration by 2030. Given the projected timing and magnitude of the morning and evening peaks of demand, the capacity value of solar is small. Similarly, the capacity value of wind is also small due to the seasonal and intermittent nature of wind generation. Biomass can add significant value to the system in terms of capacity and energy while improving the overall affordability, stability, and reliability of grid power.

We assess the capacity and energy value of biomass-based power plants on India's grid for various scenarios of installed capacity. We conclude that the total value to the grid would be lower than the levelized cost of new systems without accounting for environmental and waste management benefits. If streamlining the supply chain could reduce biomass fuel costs, and hence variable costs, the economics could be more favorable. Biomass-based systems would significantly improve the capacity value of India's 2030 projected RE resource mix (450 GW of solar-plus-wind installed capacity).

Additionally, we examine the suitability of biomass-based power plants to provide the required grid balancing services for India's 2030 grid, which is expected to have a high penetration of renewables. However, certain economic and operational constraints could hinder the use of biomass as a balancing resource. For example, diurnal balancing requires 4-6 hours of support during morning and evening peaks for more than 300 days of the year. This could be economically viable but operationally challenging for bagasse-based generation, as bagasse feedstock availability is concentrated during a few months of the year. On the other hand, combustion-based systems have ramping constraints. Biomass gasifier-based generation might not be economically viable to provide diurnal balancing either, compared with cheaper alternatives such as battery storage.

Seasonal balancing requires 60%- 80% capacity factors from October to February, which may be operationally well suited for bagasse-based generation. However, the feedstock supply chains need to be streamlined to maintain such high-capacity factors. Currently, bagasse-based generation runs at an average capacity factor of 26% between November and May. Therefore, matching the installed capacity with feedstock availability would be crucial. Bagasse-based cogeneration plants would be economically competitive vis-a-vis natural gas plants running on imported LNG to provide seasonal balancing.

India needs to weigh the advantages of deploying biomass-based power plants and consider their co-benefits while assessing the expansion of capacity.

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