CLIMATE POLICY INITIATIVE

Decarbonization of Indian Railways: Assessing Balancing Costs and Policy Risks

Charith Konda
Kuldeep Sharma
Gireesh Shrimali

April 2017

A CPI Report

Acknowledgements

The authors acknowledge the valuable contributions made by Sudhir Garg (Executive Director, Electrical, Ministry of Railways), Sudhir Saxena (CEO, Railway Energy Management Company Ltd.), Manu Srivastava (Principal Secretary & Commissioner, New and Renewable Energy Department, Govt. of MP), Ajay Shukla (Executive Engineer, Office of the Commissioner, New and Renewable Energy Department, Govt. of MP), R.K. Gupta (Director – L&R, MP Electricity Regulatory Commission), and Christoph Wolff (MD, European Climate Foundation).

This material has been funded by UK aid from the UK government; however the views expressed do not necessarily reflect the UK government's official policies. The authors also thank Vivek Sen, Saurabh Trivedi, Vinit Atal, and Chavi Meattle for participating in internal discussions, and Maggie Young, Angel Jacob, and Tim Varga for internal review.

Descriptors

Sector	Transportation
Region	India
Keywords	Decarbonization, railways, transportation, renewable energy, infrastructure
Related CPI Reports	Decarbonization of Indian Railways
Contact	Gireesh Shrimali gireesh.shrimali@cpidelhi.org

About CPI

Climate Policy Initiative is a team of analysts and advisors that works to improve the most important energy and land use policies around the world, with a particular focus on finance. An independent organization supported in part by a grant from the Open Society Foundations, CPI works in places that provide the most potential for policy impact including Brazil, China, Europe, India, Indonesia, and the United States.

Our work helps nations grow while addressing increasingly scarce resources and climate risk. This is a complex challenge in which policy plays a crucial role.

Executive Summary

Complete decarbonization of the electricity demand of Indian Railways (IR) – transitioning from the current, largely fossil-fuel based energy mix to clean energy like solar and wind power – is likely to have multiple benefits. These include support in achieving India's clean energy targets, enhancing India's energy security, and reducing IR's operational costs.

In our previous study, *Decarbonization of Indian Railways* (CPI, 2016), we assessed the economic viability of complete decarbonization of IR by 2030, and found that, for the traction segment,[1] decarbonization would be approximately 24% cheaper compared with the business-as-usual pathway in terms of average annual cash outflows. We also found that, in order to implement decarbonization, there is a need for additional analysis on load balancing options for renewable energy. Because solar and wind power can be intermittent and variable, they will require load balancing, which requires use of technologies such as energy storage to ensure consistent supply of electricity that can meet the demand.

Specifically, costs at a day-to-day management level may vary due to load balancing issues. In order to examine this issue further, in this report, we have conducted a deeper study on the pathway to decarbonization in one state, Madhya Pradesh, which is important to IR as one of the top states for electricity consumption. We assessed the total cost of 100% decarbonization of IR's traction electricity demand in Madhya Pradesh (MP), including the costs of generation and balancing, and compared that cost with the business-as-usual pathway.

Our analysis indicates that the cost of 100% decarbonization would be 26-28% cheaper than the business-as-usual pathway by 2030. These costs would reduce over time, from being 27-38% expensive in 2016-17 to being marginally expensive (2-5%) in 2022. This is largely due to an anticipated continuous decrease in renewable energy costs. The business-as-usual pathway, which is the average power procurement cost of DISCOMs in India and reflects the country's energy mix (dominated by fossil fuel-based energy), will be impacted negatively due to the expected continuous increase in fossil fuel costs.

We also found that balancing costs will likely account for 5-8% of the total decarbonization costs in 2030, depending on the balancing technology chosen.[2] These costs are bound to gradually reduce from 5-12% in 2016-17 and 5-9% in 2022 as balancing technology costs (specifically, of grid-scale batteries) are expected to reduce in the next 10-15 years due to advancement in battery storage technology.[3]

Because of this, IR should aim to gradually ramp up the rate of decarbonization, accelerating from 2022, and achieve 100% decarbonization by 2030. By 2030, the cost savings of decarbonization compared to the business-as-usual pathway will become quite apparent. The more promising balancing technologies, such as grid-scale battery storage, are also expected to be commercially viable by 2030.

Balancing costs are minimized by using an optimal mix of largely wind power and some solar power. We found that there would be a significant reduction in balancing costs as a percentage of the total cost by using an optimal mix of wind and solar power. Under a scenario of decarbonization via all solar power, the balancing cost percentage of total costs increases to 63-78% from 5-8% in the wind and solar optimal mix scenario. Though the generation costs will be lower in an all solar scenario (due to lower per unit generation cost of solar power compared with wind power), the cost-effectiveness of solar power relies heavily on the availability of a large-volume, low-cost balancing option. This is because balancing electricity units as a proportion of total renewable electricity units generated increases from around 4% (or 0.4 million units daily) in a mixed wind and solar scenario to about 58% (or 6.2 million units daily) in an all solar scenario.

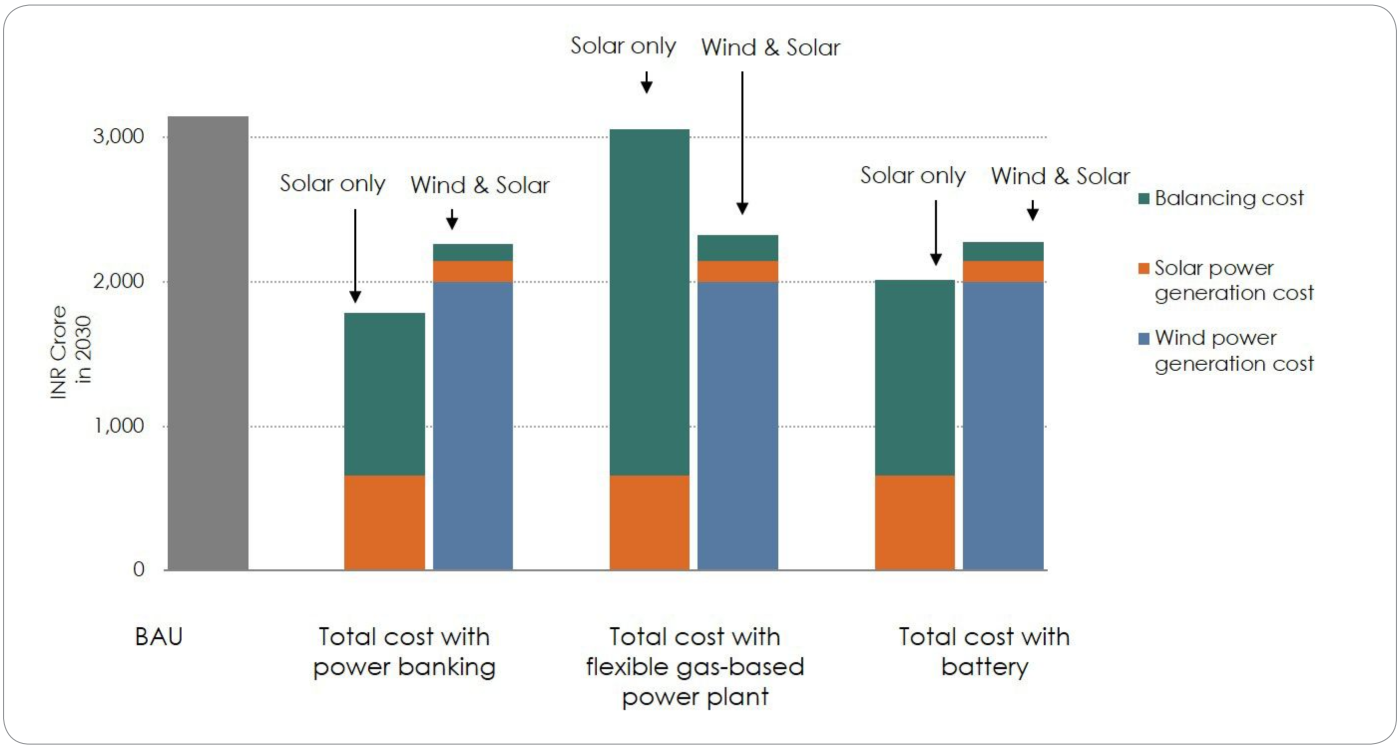
We recommend that IR adopt a wind and solar mix, given the low possibility of finding such a high-volume,

1 The electricity consumption resulting from moving trains is categorized as traction electricity demand, while the electricity consumption from railway stations and other buildings is categorized as non-traction electricity demand.

2 We have chosen the balancing options of power banking with other DISCOMs or power traders, a flexible gas-based power plant, and a grid-scale lithium ion battery storage based on our analysis in CPI, 2016.

3 While balancing need (in terms of electricity units) is doubling between 2016-17 and 2030 due to increasing demand, this is offset by the expected decrease in balancing technology costs, specifically of batteries. Battery storage may turn out to be a better investment in the long-run due to lower risks and more flexibility. Power banking is dependent on finding a suitable partner and grid scheduling issues, while gas-based power will be subject to fuel availability and risk of adverse movement of gas prices. We note that there is a need to further analyze the balancing costs as these costs are dependent on several other factors, including the expected change in country's energy mix, demand for balancing services etc. Balancing cost estimates in this report can be considered as preliminary estimates.

Costs of decarbonization under different balancing options



low-cost balancing arrangement. The balancing need is low in a mixed wind and solar scenario as wind power's generation profile is not only better correlated with demand,[4] it is also complementary with solar power's generation profile.

Costs of decarbonization under different balancing options

In terms of IR's energy capacity requirement to meet its electricity demand, IR will require a total installed solar and wind capacity of approximately six times its demand, given the average capacity utilization factors (CUFs) of solar and wind, which are in the range of 18-19%. Further, we found that IR will require the installed wind capacity to be approximately eight times more than that of solar to keep the balancing need and costs low.

However, while planning for 100% decarbonization, IR should keep in mind the seasonality of wind power in India. Wind is seasonal in India. It can lead to -19% to +32% variation in the total capacity requirement during the worst case (October-December) and best case (May-September) scenarios to meet IR's electricity demand. While keeping the capacity constant (at a base case), we found that the energy generated could vary from a shortfall of 23% to a surplus of 25% compared to the energy generated from the annual average CUF. This further indicates that IR might require a seasonal power banking arrangement in addition to intra-day power banking to manage the seasonality of wind. Although, it must be noted that the impact of seasonality can be accurately predicted only through a probabilistic simulation model.

Finally, IR must recognize the policy and regulatory risks of decarbonization and plan to mitigate them effectively. The top policy and regulatory risks that IR might face include a lack of states' recognition of IR's deemed transmission and distribution licensee status and the lack of a suitable power banking arrangement. Other potential risks are delay in implementation of a framework that enables the inter-state sale of renewable energy and delay in development of a national balancing market. Short-term measures, such as directly connecting to an inter-state transmission network to gain more operational freedom, and long-term measures, such as policy advocacy to drive the development of national/regional balancing markets, could be used to mitigate these risks.

4 The correlation between wind generation and IR's electricity demand is 0.26, while the correlation between solar generation and IR's electricity demand is only 0.02.

Contents

1. Introduction

Indian Railways (IR) is the single largest electricity consumer in India. Decarbonizing Indian Railways would not only help India achieve its clean energy targets but also increase energy security by reducing fossil fuel imports. Further, decarbonization would be most likely cost-effective in the long run, given the falling costs of renewable energy and increasing costs of fossil fuel-based power (CPI, 2016).

In the first part of our study, *Decarbonization of Indian Railways*, (CPI, 2016) we examined the costs of decarbonization at a macro level and on an annual basis in terms of cash outflows under different decarbonization pathways. We found that decarbonization of IR by 2030 would be cheaper than a business-as-usual pathway, but in order to implement decarbonization, there is a need for low-cost and feasible balancing options[5] for renewable energy.

Specifically, we were also cognizant of the possibility that costs at a day-to-day management level may vary due to load balancing issues since wind and solar power generation is variable. In order to examine this issue further, in this report, we have conducted a deeper study on the pathway to decarbonization in one state, Madhya Pradesh, which is important to IR as one of the top states for electricity consumption. We assessed the wind and solar power requirement for decarbonization by 2030, as well as the balancing costs over a 24-hour period in a cost-optimized manner to achieve 100% decarbonization of IR's traction electricity demand in Madhya Pradesh.

We assessed these costs on a levelized cost basis assuming IR could sign a 25-year power purchase contract with wind and solar power producers at three different time periods: 2016-17, 2022, and 2030. We also examined the potential policy and regulatory risks that could impact the decarbonization plans of Indian Railways and discussed possible solutions to mitigate these risks.

In Section 2, we have highlighted our approach towards tackling the problem of estimating the decarbonization costs, the components of decarbonization costs, the required wind and solar power generation capacities for achieving 100% decarbonization, and finally the total costs of decarbonization (including the costs of balancing). In Section 3, we have examined the policy and regulatory risks that could hinder the decarbonization plans of IR, and have suggested potential solutions to mitigate the key risks identified. In Section 4, we have listed our recommendations for IR and topics for future work.

We believe this short study will set the stage for a more elaborate assessment of the load balancing requirement, which could be based on a probabilistic simulation model considering time periods of 15 minutes blocks over 24 hours and 365 days. Additionally, future work may require an assessment on the required capital expenditure for a complete system design, including new transmission infrastructure and battery storage system.

5 A power system which has a high share of variable renewable energy, such as wind and solar power, needs to be balanced – i.e. the variable power generation has to be matched with demand at all times.

2. Decarbonizing Indian Railways

Decarbonization of Indian Railways (IR) would mean that IR meet its energy requirements through non-fossil fuel-based clean energy sources. Decarbonization of operations could be predominantly done through the use of clean and renewable energy sources, such as wind, solar, hydro, nuclear, and biofuels. In CPI, 2016, we highlighted how wind and solar energy are the most feasible and cost-effective large-scale clean power sources among the options available.[6]

2.1 Load balancing

The primary challenge faced by IR while using high shares of variable renewable energy, such as wind and solar power, is meeting their electricity demand at all times irrespective of the variability in power generation. Additionally, if IR is aiming for 100% decarbonization, it should not only be able to generate and consume adequate clean energy, but also generate and store surplus power to meet shortfalls. This surplus power can be stored in balancing options to draw equivalent quantities when there is a shortfall in generation—such as a power banking arrangement with DISCOMs (India's state-level public electricity distribution companies) or other traders or in a battery. This way, IR could achieve 100% decarbonization on a net energy basis.

In this report, we have considered the generation costs and balancing costs associated with the balancing options of power banking with other DISCOMs or power traders, a flexible gas-based power plant, and a grid-scale lithium ion battery storage. These were selected from the commercial, technical, and regulatory feasibility analysis that we undertook in CPI, 2016. We have compared the total costs of decarbonization (generation plus balancing) with the business-as-usual cost to determine whether a complete decarbonization pathway would be more cost-effective for IR.

2.2 Decarbonization costs

We have estimated the decarbonization costs at three different time points – 2016/17, 2022, and 2030 – using wind and solar with three different balancing technologies – power banking, a flexible gas-based power plant, and battery storage. For the purpose of analysis in this paper, we have considered the decarbonization costs to be the cost of renewable energy (i.e., levelized cost of wind and solar power) plus the balancing cost (per kWh cost of balancing technology) required to meet 100% electricity demand of IR in a given year (Appendix 5.1).

2.2.1 DECARBONIZATION COSTS BASED ON ANNUAL AVERAGE CAPACITY UTILIZATION FACTORS

First, we estimated the decarbonization costs based on the annual average capacity utilization factors (CUFs) of wind and solar power. Using a cost optimization model, we found that:

100% decarbonization costs will be 26-28% cheaper than business-as-usual by 2030, progressing from being 27-38% more expensive than business-as-usual in 2016-17 and marginally more expensive (2-5%) in 2022 (Figure 1).[7] The increase in the cost of business-as-usual is largely due to increasing fossil fuel costs,[8] while the decrease in decarbonization costs are primarily due to falling renewable energy (wind and solar) and battery storage costs. The increase in cost across all categories is due to IR's growing electricity demand, which is expected to increase at a compound annual growth rate (CAGR) of 6% from 2016 to 2030, driven by increasing electrification and traffic.

2.2.2 BALANCING COSTS

Balancing costs will likely account for 5-8% of the total decarbonization costs by 2030, if they continue to reduce as expected from 5-12% in 2016-17 and 5-9% in 2022, due to expected reductions in balancing technology costs (Figure 2). While the balancing needs (in terms of electricity units) will double between 2016-17 and 2030 due to increasing electricity demand, this will be offset by the expected decrease in balancing technology costs, specifically of batteries.[9] Overall, balancing costs will likely account for approximately 10% (or less) of the total decarbonization costs during

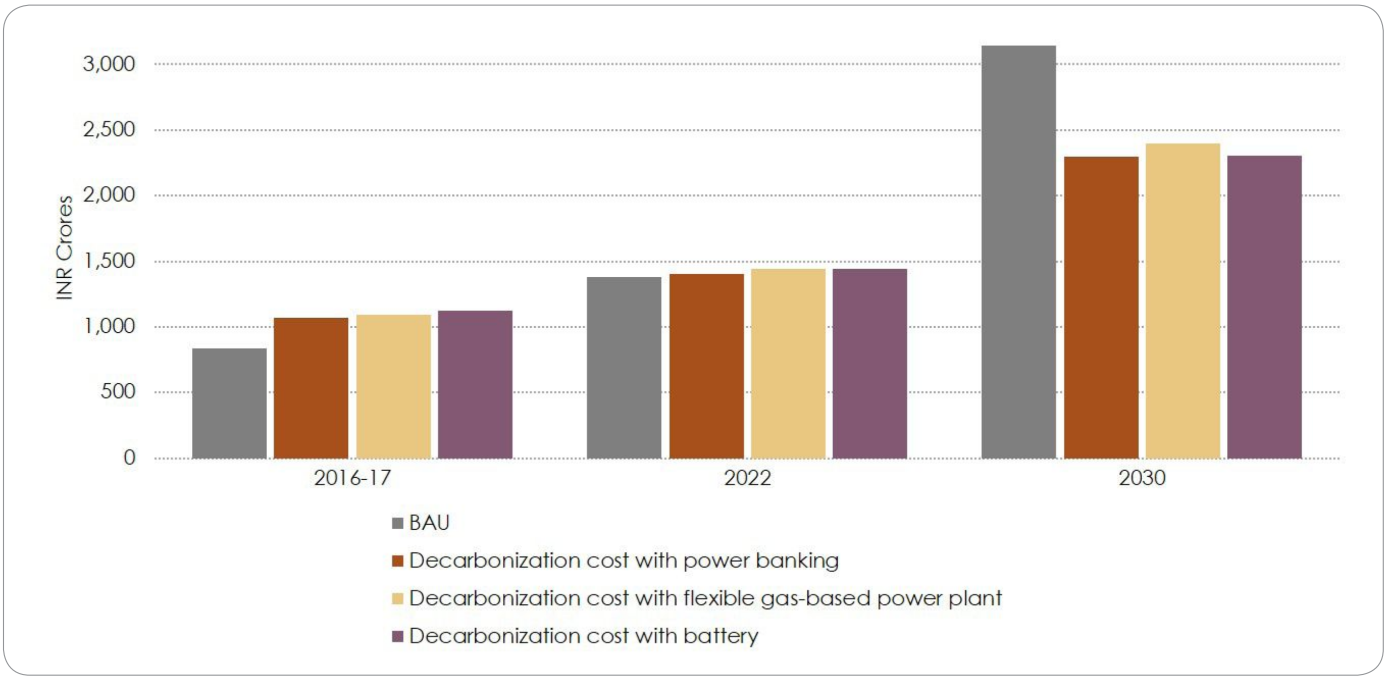
6 In CPI, 2016, Decarbonization of Indian Railways, we determined that electrification of IR's traction operations is a prerequisite for decarbonizing its operations. By the end of 2016, 42% of the total track network is electrified, which accounts for approximately 75% of the freight traffic and 50% of the passenger traffic (PIB, 2016). Regardless of its decarbonization plans, Indian Railways has set itself a target of electrifying more than 90% of its tracks in the next 5 years.

7 Decarbonization costs were estimated based on LCOEs derived from a standard project financing model of independent power producers. IR could further lower the costs of decarbonization through either investing in their own plants (IR's cost of capital will be much lower than IPP's cost of capital) or through inviting competitive bids, which encourage financial and business innovation to lower the costs.

8 We forecasted the business-as-usual costs in CPI, 2016 (Appendix 5.2). We have used the same forecast in this study as well.

9 We have discussed the methodology for estimating the balancing costs in detail in Appendix 5.4.

Figure 1: Decarbonization costs with different balancing options

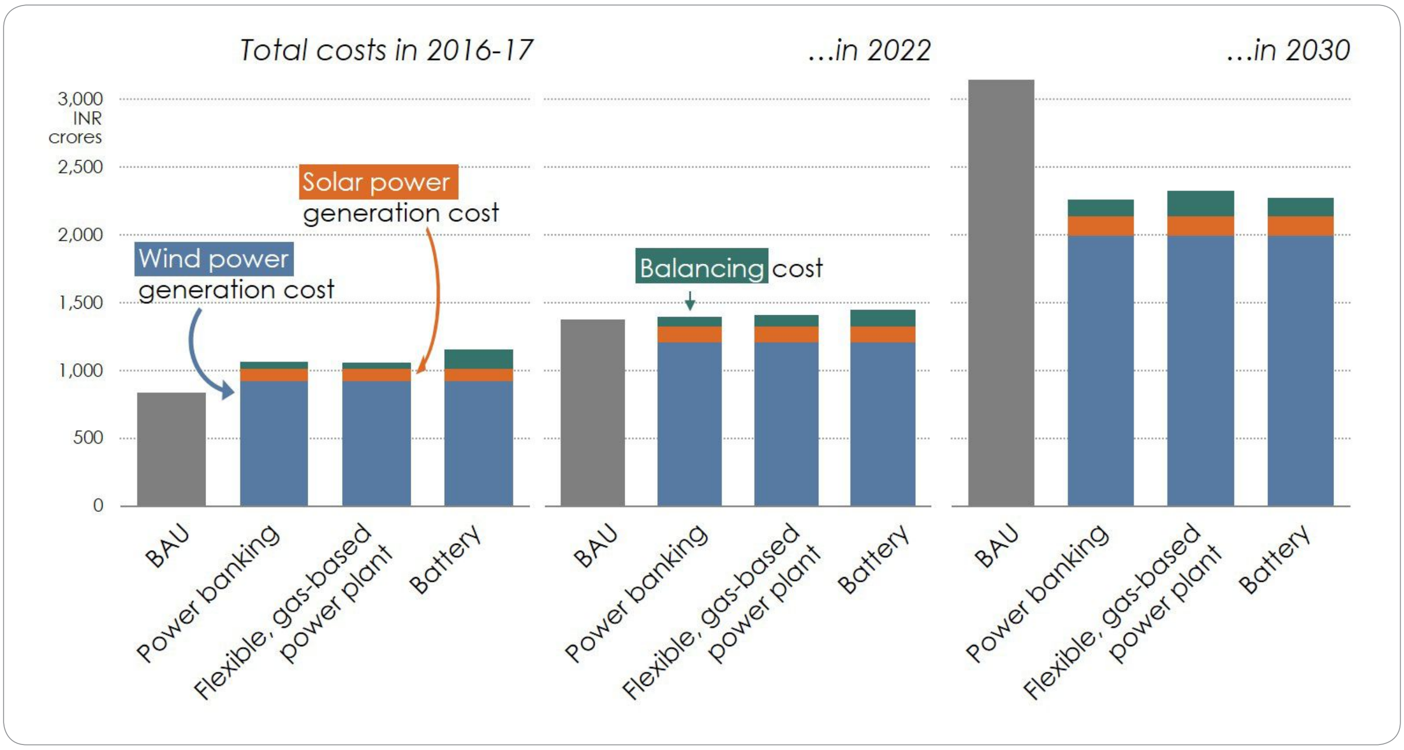


2016-2030, as the majority of the balancing need would be addressed by the complementary generation profiles of between the wind and solar power.

In terms of the cost-effectiveness of the different balancing options, a power banking arrangement with another DISCOM or a power trader (energy to energy basis with transmission and distribution charges and losses as sole expenses) would perhaps be the cheapest balancing option across 2016 to 2030. Finding a party who has an opposite load profile or energy needs to that of Indian Railways would be key in this scenario.

Also, battery storage may turn out to be a viable investment in the long-run due to expected reduction in technology costs. Although at present grid-scale lithium-ion battery storage costs are more than 100% higher than gas-based balancing costs on a kWh

Figure 2: Cost of decarbonization, by component



basis (2016-17), battery storage costs are expected to fall sharply (10-12% annually)[10], almost erasing the difference in costs with gas-based power in 2022, and turning out to nearly 80% cheaper than gas-based power by 2030 (Appendix 5.1). Further, battery storage has lower operational risks and provides more flexibility while power banking is dependent on finding a suitable partner and grid scheduling issues and gas-based power will be subject to fuel availability and risk of adverse movement of gas prices.[11]

Because of this, IR should aim to gradually ramp up the rate of decarbonization, accelerate from 2022, and achieve 100% decarbonization by 2030. By 2030, the cost savings of decarbonization compared to the business-as-usual pathway will become quite apparent. The more promising balancing technologies, such as grid-scale battery storage, are also expected to be commercially viable by 2030. There is even a possibility that 100% decarbonization will be cheaper than the business-as-usual pathway by 2022, if IR adopts a competitive electricity procurement process.[12]

In our model of decarbonization costs (Figure 2), wind power generation accounts for the majority of the cost of decarbonization. Our model allocates higher capacity to wind power despite a lower per kWh cost of solar power because wind power has a better generation profile and has the potential to reduce the overall IR's power system cost, which we discuss in further detail later.

2.3 Wind and solar power capacity requirement

To estimate the amount of installed wind and solar power capacity that will be required to meet IR's given electricity demand, we first tried to estimate the typical wind and solar generation profiles in the state of Madhya Pradesh. However, due to lack of data in Madhya Pradesh, we gathered data from the neighboring states of Maharashtra and Gujarat.[13] We derived the generation profiles of wind and solar at the grid level, based on average annual capacity utilization factors (CUFs), which is 19% for wind and 18% for solar (Appendix 5.3). We derived the capacities for each year through our optimization model, which optimizes the capacity based on the generation profiles and cost of generation. Our key findings are:

Table 1: Expected electricity demand and generation capacity required

	2016-17	2022	2030
WIND CAPACITY (MW)	1,137	1,613	2,571
SOLAR CAPACITY (MW)	145	205	327
TOTAL CAPACITY (MW)	1,282	1,818	2,898
ELECTRICITY DEMAND (MWH)	200	284	452

To decarbonize 100% of IR's electricity demand, IR would need to install a renewable energy capacity of approximately six times more than its demand (Table 1). In 2016-17, IR would need an installed capacity (wind and solar combined) of 1,282 MW. Similarly, it would need a total installed capacity of 1,818 MW in 2022 and 2,898 MW in 2030. This is primarily because of the CUFs of solar and wind, which are on average in the range of 18-19%.

Further, we found that IR will require the installed wind capacity to be approximately eight times more than that of solar to keep the balancing need and costs low. This is because wind has a better power generation profile, as there is more availability on average over the 24-hour day, and it matches electricity demand in a better way than solar power. Our analysis indicated a correlation of 0.26 between wind generation and IR's demand, while solar generation had a correlation of only 0.02.

To meet the objective of 100% decarbonization, the power system designed by our optimization model generates surplus power when the resources (wind and sun) are available, to feed the power into balancing options, such as power banking and battery storage (Figure 3). In the case of a gas-based power plant, the surplus power can be sold via power exchanges. Our model ensures that the surplus generation is greater

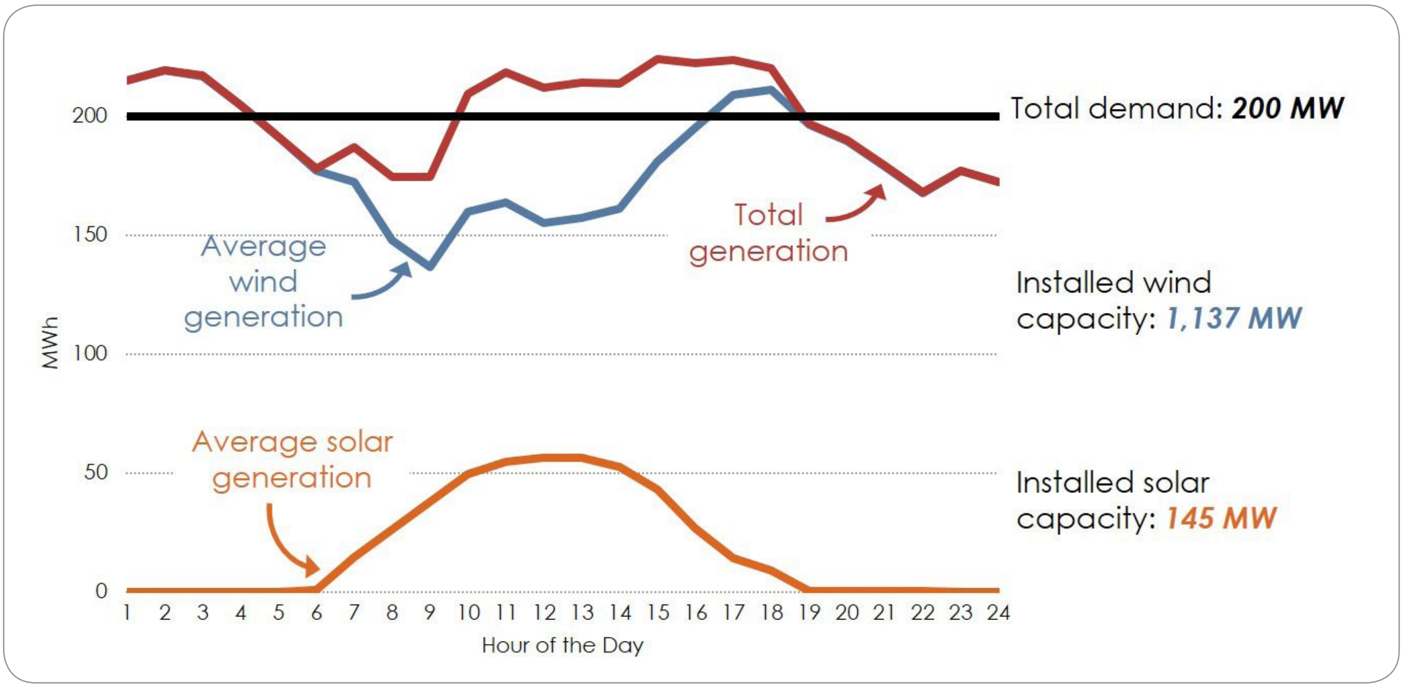
10 BNEF, 2016 and GS, 2015

11 We note that further work is required to accurately estimate the battery costs. In this study, we derived battery costs from secondary research. However, battery costs may vary widely by region, by application, and by the type of battery used – even among the lithium ion batteries, the life of the batteries may vary from 5 to 15 years. Regardless, several studies indicate a drastic reduction in battery storage costs in the next 5-10 years (IHS, 2015; Reuters, 2016).

12 Our cost estimates were based on standard return expectations and cost of capital of independent power producers (Appendix 5.1). However, the costs discovered through a competitive bidding process may turn out to be much lower as bidders may reduce their return expectations and deploy innovative financing mechanisms to win projects.

13 IR need not necessarily generate wind and solar power in Madhya Pradesh for consumption. While generating in Madhya Pradesh itself may lead to lower transmission and distributions costs, better CUFs and generation profiles (especially for wind in Maharashtra and Gujarat) may make it more cost-effective to generate power in other states and consume in Madhya Pradesh.

Figure 3: Wind and solar generation profile on an average day in Madhya Pradesh



than or equal to the shortfall in generation to achieve 100% decarbonization on a net energy basis.

2.4 Seasonality of wind

While planning for 100% decarbonization, it's important that IR should keep in mind the seasonality of wind power in India. The velocity of wind varies by the season, which affects wind power generation. An observation of wind speeds in the top five wind potential states in India (Andhra Pradesh, Karnataka, Tamil Nadu, Gujarat, and Maharashtra) indicated that India has three wind seasons: Jan-Apr (low-wind season), May-Sept (high-wind season), and Oct-Dec (very low-wind season) with significant variation in CUFs (Phadke A., et al., 2011).

Variation in CUFs could result in a different power generation capacity requirement than what we have estimated using the annual average CUFs. To evaluate the impact of seasonality, we tested the sensitivity of

Figure 4: Wind generation by season

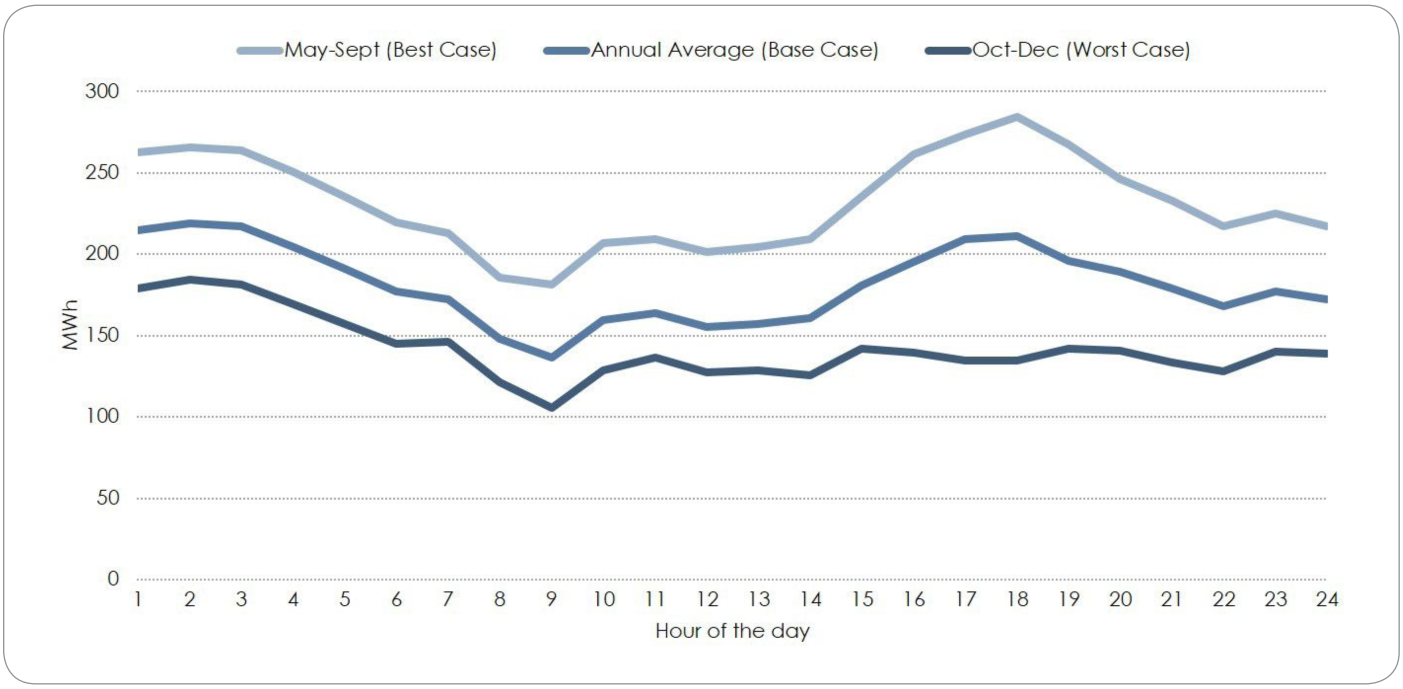


Table 2: Sensitivity of results to wind seasonality

2016-17	BASE CASE	% OF TOTAL CAPACITY	BEST CASE	% OF TOTAL CAPACITY	% CHANGE IN CAPACITY FROM BASE CASE	WORST CASE	% OF TOTAL CAPACITY	% CHANGE IN CAPACITY FROM BASE CASE
Wind capacity (MW)	1,137	89%	882	85%	-22%	1,452	86%	28%
Solar capacity (MW)	145	11%	156	15%	8%	236	14%	63%
Total capacity (MW)	**1,282**	**100%**	**1,038**	**100%**	**-19%**	**1,688**	**100%**	**32%**

our results (Table 1) to the changing CUFs of wind as per the seasons identified above. And for evaluating the seasonality associated with wind power generation, we used the hourly wind generation data of Maharashtra and Gujarat from 2015.[14] We divided the year into three seasons (as identified above) and took an hourly average of the power generation for these seasons.

We found that the average CUFs for wind power vary by season in the following fashion: January-April: 12.86%, May-September: 20.41%, and October-December: 12.49%. We derived three different generation profiles relevant to these seasons (Figure 4). Clearly the October-December quarter of the year is the worst, while May-September is the best season for wind. Hence, we tested the sensitivity of our results to the data of May-September and October-December seasons with our annual average data (base case), which has the average CUF of 16% through the day.[15] For 2016-17, with the given CUFs, we determined the following generation profiles:

With the above generation profiles, our optimization model yielded the below power generation capacity requirement results (Table 2). We kept the solar generation profile constant through the year for the purpose of this analysis.

The total capacity required for meeting IR's electricity demand decreases by 19% under a best case scenario (the high wind generation period of May-Sept), compared to the base case scenario (the annual average). The required installed solar capacity would increase by 8% and the required installed wind capacity would decrease by 22%, compared to the base case scenario. The overall capacity requirement decreases due to an improved CUF of wind power compared with base case.

Under the worst case scenario (the low wind generation period of Oct-Dec), the total capacity required for meeting IR's electricity demand increases by 32% in comparison to the base case scenario. The installed solar capacity increases by 63% while the installed wind capacity increases by 28%, as compared to the base case scenario. The overall capacity requirement increases due to a reduction in the CUF of wind power from the base case.

Wind power's share of the total mix decreases by only 3 percentage points from the base case scenario to the worst case scenario, even though the average CUFs decrease from 19% to 12.49%. As previously discussed, it is possibly because of the better correlation of wind generation with the electricity demand of IR.

The overall results of the report are consistent with our expectations, as the total required installed capacity increases during the worst season for wind generation and decreases during the best season for wind generation. This analysis will only be marginally better than our annual average (base case), as seasonality can be predicted accurately only through a 15-minute time interval, 24-hour, 365-day, probabilistic simulation model.

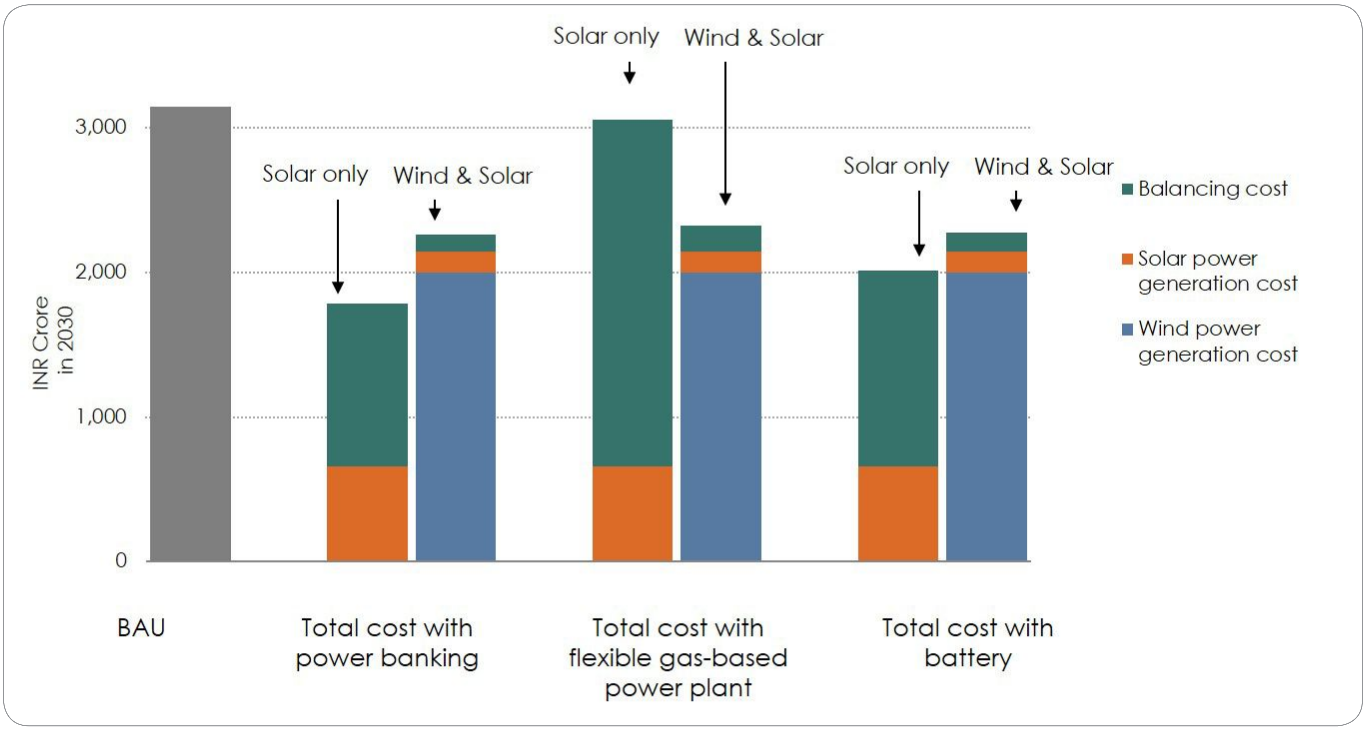
We also tested how the generation profile of our base case capacity would vary with the seasons (by changing the CUFs) and found that there will be a surplus of 25.3% during May-September (best case) and a shortfall of 23.3% during October-December (worst case) and overall surplus of 2% during the year compared to the generation derived from a constant annual average CUF.

Hence, our base case capacity could serve as an optimal capacity. But given the variations in generation, IR may have to opt for a seasonal power banking arrangement in addition to an intra-day power banking arrangement. However, the actual requirement (in terms of volume) of seasonal power banking and the costs associated with seasonality of wind could only be estimated through a probabilistic simulation model and requires further work.

14 These states were chosen because of their proximity to MP and availability of data. The data was extracted from the daily generation reports provided by the respective states' Load Dispatch Centers. As noted earlier, generation profile data of wind and solar are not available for Madhya Pradesh.

15 The base case is the average of all the three seasons.

Figure 5: Comparison of decarbonization costs, by balancing technology



2.5 Reducing costs via an optimal mix of wind and solar energy

As mentioned briefly earlier in the report, **IR can keep balancing costs low by using an optimal mix of largely wind power and some solar power, as opposed to using just solar power.**

We found that that the total cost of decarbonization if IR uses just solar power will be in the range of INR 1,785-3,056 crores (Figure 5) compared to the total cost of decarbonization under a mix of wind and solar power, at INR 2,260-2,324 crores (Figure 2) in 2030. The lower end represents the decarbonization costs with a power banking option and the higher end represents the costs with a flexible gas-based power plant as a balancing option.

While the generation costs are lower in the only solar scenario (at 22-37% of the total costs) compared to the wind and solar mix scenario (at 92-95% of the total costs), balancing costs account for a larger share (63-78%) of the total costs in the only solar scenario compared to the balancing cost share of 5-8% in the wind and solar mix scenario.

Though the generation costs will be lower in an only solar scenario, due to lower per kWh costs of generation of solar power compared to per kWh cost of generation of wind power, balancing costs increase in the former due to higher balancing needs since solar power is available only for ~8 hours in a day.[16] Balancing electricity units as a proportion of total renewable electricity units generated increases from around 4% in a mixed wind and solar scenario to about 57% in an only solar scenario. Balancing costs are lower in the wind and solar scenario due to complementary nature of wind and solar generation profiles.

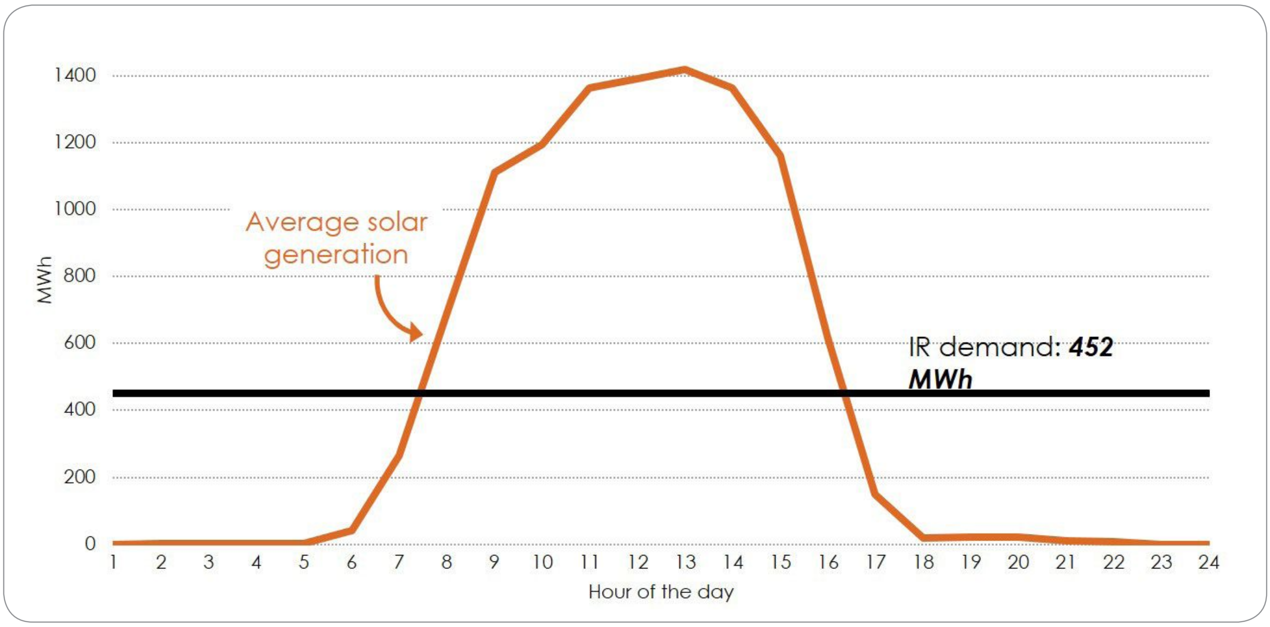
The cost-effectiveness of an only solar scenario would rely heavily on the availability of a large-volume, low-cost balancing option. **We recommend that IR adopt a wind and solar mix to keep decarbonization costs low, given the risks and low possibility of finding such a high-volume, low-cost balancing arrangement for an all solar power scenario.**

We also found that if IR opts for only solar instead of a combination of wind and solar to meet the demand of 452 MWh in 2030, it will require a solar power generation capacity of 2,840 MW. At this capacity, the solar generation profile is as below:

Though the total generation capacity required in the only solar scenario is in a similar range to that of solar and wind scenario, the balancing need drastically increases in the only solar scenario as noted above.

16 Surplus power has to be generated and stored in large quantities during the day, so it can be used at night.

Figure 6: Only solar generation profile



3. Policy and regulatory risks to decarbonization

One of the primary concerns of Indian Railways (IR) in adopting a high decarbonization plan is the possibility of an increase in costs due to policy and regulatory risks. Though a few of these risks may be common for both business-as-usual and decarbonization pathways, some risks may exacerbate under a decarbonization pathway.

From discussions with relevant stakeholders,[17] we identified major policy risks that will be relevant to IR and also estimated the potential impact of these risks. We note that a thorough policy landscape analysis (perhaps at a regional level) is essential to identify the policy/regulatory risks and potential solutions in a more rigorous manner.

Through our consultations, **we found the following top policy and regulatory risks**:

1. A lack of recognition of IR's deemed transmission & distribution licensee status by states may constrain IR's operational freedom. This is largely due to the reluctance shown by DISCOMs toward losing their most valuable and credible consumer, IR. This lack of recognition of IR's T&D licensee status would limit IR's freedom in competitively procuring electricity and building its own transmission and distribution lines.
2. Uncertainty over IR's ability to find a power banking arrangement under the licensee model either within or outside Madhya Pradesh (via open access) would remove a low-cost balancing option and would most likely increase the costs of decarbonization.
3. A delay in implementation of the framework that enables inter-state sale of renewable energy and development of a national balancing market also poses a risk, for several reasons. First, a delay in introducing a framework for inter-state sale of renewable energy will limit IR's ability to generate renewable energy in other states (which have good resources) and transmit to its demand centers. This will possibly increase the costs of generation. Second, if the development of a national balancing market gets delayed, IR will have to develop its own balancing option, such as battery storage or a flexible thermal power plant. This will also increase the cost of decarbonization.

Table 3 below lists all of the risks we identified (Appendix 5.5).

Suggested measures to mitigate risks:

IR could adopt a set of short-term and long-term measures (Table 4) to mitigate risks, which were identified through stakeholder consultations and secondary research.

17 We had discussions with IR officials and Madhya Pradesh state government officials, including the Principal Secretary and Executive Engineer – New and Renewable Energy Department, and officials of the Madhya Pradesh Electricity Regulatory Commission. We have defined and indicated the individual scores of the risks in Table 5 in Appendix 5.4.

Table 3: Policy risk matrix

		IMPACT ON DECARBONIZATION		
		LOW	MEDIUM	HIGH
PROBABILITY	HIGH (1.0)		• Delay in introducing framework for forecasting, scheduling & imbalance handling for renewable energy at the inter-state level	• Hurdles in operationalizing IR's deemed T&D licensee status • Lack of power banking under the transmission and distribution licensee model
	MEDIUM (0.5)		• Delay in developing a balancing market	• Lack of open access to procure electricity from supplier of choice.
	LOW (0.1)	• Lack of or delay in building new T&D infrastructure by the state • Reduction in national renewable energy targets	• Delay in approvals/permits for constructing renewable power plants. • Delay in introducing renewable energy trading on exchanges • Grid congestion	

Table 4: Risk mitigation measures

RISKS	SHORT-TERM MITIGATION MEASURES	LONG-TERM MITIGATION MEASURES
State DISCOMs not recognizing IR's deemed T&D licensee status and thereby refusing open access and/or a power banking arrangement	• Connect directly with the Inter-State Transmission System (ISTS).[a] This may require building of new transmission lines for connecting IR's sub-stations with the ISTS in some regions.	• Push for regulatory relief from the central government or from state regulatory commissions for recognition of deemed T&D licensee status by the state governments.
Lack of a power banking arrangement	• Explore all potential ways of getting a power banking arrangement – » Within the state, work with the Madhya Pradesh Power Management Company » Outside the state, consult with other power traders and state DISCOMS. Evaluate the possibility of issuing a power banking tender similar to the Delhi DISCOMs (BSES, 2015).	• Develop other balancing options such as battery storage or a flexible gas-based power plant or pumped hydro storage. • Push for finalization of enabling policies for renewable energy power trading on exchanges.
Delay in introducing framework for forecasting, scheduling & imbalance handling for renewable energy	• Work within the existing intra-state forecasting and scheduling frameworks.	• Work with Central Electricity Regulatory Commission and other relevant ministries for finalizing and operationalizing of a forecasting and scheduling framework for both intra-state and inter-state sale of renewable energy.
Delay in developing the balancing market	• Develop in-house balancing options such as battery storage or use existing thermal plants for balancing.	• Undertake policy advocacy for the development of a national/regional balancing market, such as development of regional level spinning/primary, secondary, and tertiary reserves.[b]

a Which is largely controlled by Power Grid, a central government entity.

b As laid out in CERC, 2015a

Sources: Consultations with REMCL, MPNRED, MPERC, BSES, 2015, CERC, 2015b

4. Conclusion

In this report, we have assessed the total cost of 100% decarbonization of IR's electricity demand in Madhya Pradesh, including the costs of generation and balancing, and compared that cost with the business-as-usual pathway, in order to gain a deeper understanding of the potential effect of balancing costs on the overall costs of decarbonization.

We found that complete decarbonization of Indian Railways' electricity demand will possibly be more cost-effective than the business-as-usual pathway in the long-run even after including balancing costs. Based on the analysis in this report, our recommendations are as follows:

- Indian Railways (IR) should aim for 100% decarbonization of electricity demand in the traction segment in Madhya Pradesh by 2030, as a decarbonization pathway will be 26-28% cheaper than the business-as-usual pathway.
- IR should consider accelerating decarbonization after 2022 when the cost savings will become quite apparent, and move towards achieving the 100% decarbonization target by 2030.
- Balancing costs can be minimized by using an optimal mix of largely wind power and some solar power, as opposed to just solar power. This is because the generation profiles of wind and solar are complementary and the wind generation profile is better correlated with demand, resulting in lower overall balancing costs.
- When planning for decarbonization, IR should keep in mind that wind is seasonal in India, which can cause a variation of -19% to +32% in the installed wind capacity that would be required to complete decarbonization by 2030. However, a robust probabilistic simulation model may be required to accurately predict wind seasonality and its impact on costs.
- IR should make strong efforts to operationalize their deemed transmission and distribution licensee status in order to gain more operational freedom, but should expect some drawbacks in the form of lack of a power banking arrangement with state DISCOMs (in the traditional fashion) and the ability to use the state grid.
- IR should explore new balancing mechanisms under the licensee model, including trade of renewable power and sourcing power banking arrangements competitively.

5. Appendix

5.1 Per unit cost of decarbonization

In Table 4, we indicated the per unit (kWh) cost of each technology we used for decarbonization. These costs were inputs to our cost-optimization model by which we determined the required installed capacity of wind and solar energy. Below are some of the assumptions on which these costs were calculated:

Table 5: Per unit costs of decarbonization

COSTS (INR/KWH)	2016	2022	2030
Wind power	6.10	5.64	5.84
Solar power	5.65	5.09	3.93
Power banking	1	1	1
Gas-based power	6.15	7.81	10.51
Battery storage	12.4	5.7	2
Business-as-usual	4.78	5.98	7.93

Sources: CPI, 2016; BNEF, 2016; GS, 2015

1. Wind and solar levelized cost of energy (LCOE) forecasts are CPI's own estimates (CPI, 2016). These were drawn from the latest CERC's assumptions to determine the benchmark tariffs for wind and solar power plants. These forecasts are based on business fundamentals as we did not include the prices that IR could achieve via competitive bidding, which could possibly be much lower than our forecasted prices.
2. Historically, as a consumer of the Madhya Pradesh DISCOM, Indian Railways could get a power banking arrangement for as low as INR 0.10/kWh. With the current status of a deemed transmission and distribution licensee, this cost is expected to increase. IR may likely enter into an energy swapping arrangement with other DISCOMs within the state or outside the state or with a power trader. As long as the energy exchanged stays within the agreed quantity, neither party needs to pay energy charges. In this case, only wheeling and some additional charges for providing banking service may be required to be paid by IR. Typically, these charges amount to INR 0.41-0.47/kWh. For this study, we have considered the higher end of the charges – i.e., INR 1/kWh, but kept this constant across different time periods.
3. Gas-based power cost in 2016 is the unsubsidized cost per unit from the Ratnagiri Gas-based Power Plant (RGGPL) plant that IR received. We extended this price using wholesale price index (WPI) inflation forecast to estimate the gas-based power price for 2022 and 2030.
4. Grid-scale lithium-ion battery storage costs are expected to reduce by 10-12% every year until 2030 (BNEF, 2016 and GS, 2015). We reduced the battery costs at 12% CAGR starting 2016.
5. Business-as-usual costs are as estimated in CPI, 2016.
6. Key assumptions for estimating the levelized costs of wind and solar power: Our LCOE model assumptions were based on standard return expectations and cost of capital of independent power producers in India. These costs may vary from the competitively bid prices.

Table 6: Key assumptions for estimating the costs of wind and solar power

PARTICULARS	UNITS	SOLAR	WIND
Capacity Utilizations	Best Case %	18%	22%
	Base Case %	18%	19%
	Worst Case %	18%	12%
Total Auxiliary Consumption	%	0%	0%
Useful Life	Years	25	25
Part of Auxiliary Consumption received from Grid	%	0%	0%
Cost of auxiliary power purchased from grid	INR/kWh	4	4
Capital Cost (incl Interest During Construction)	Rs. Cr. /MW	5.28	6.19
Capital Subsidy	Rs. In Cr	0	0
Payables	Days	30	30
Receivables	Days	60	60
Spare & Maintenance (Inventory)	O&M Expenses	15%	15%
Escalation in O & M Expenses	%	4%	4%
O & M Expenses/MW (1st Year)	Rs. In Lacs	7.27	11.24
Interest On LT Loan Outstanding (Payable)	Days	30	30
Interest Rate	%	12.76%	12.76%
Repayment Period (incl. Moratorium Period)	Years	12	12
Expected Return on Equity	%	16%	16%

5.2 Estimation of business-as-usual costs

We defined the business-as-usual pathway for the traction segment of IR as the average power procurement cost of DISCOMs in India. We assumed IR, as a deemed transmission and distribution licensee, would mimic the power procurement strategies of other DISCOMs in India. DISCOMs procure power as competitively as possible, and because of DISCOMs' expertise and market presence, it is unlikely IR can procure power more competitively than DISCOMs. Therefore, taking the average power procurement cost of DISCOMs in India as the business-as-usual pathway for IR is the most competitive benchmark to compare decarbonization costs against.

We forecasted the cost of the business-as-usual pathway to 2030, using three different methods:

- *Inflation-based forecast*: We used a consumer price index inflation rate as the escalation factor to forecast the average power purchase cost and commercial tariffs. Here, we assumed that the average power purchase cost and the commercial tariffs would grow at the rate of inflation in future.
- *Linear trend*: We used the linear trend extrapolation approach to forecast the average power purchase cost and commercial tariffs. Here, we assumed that business-as-usual applicable will follow the linear fit to historical trend in the future.
- *Regression approach*: We used two factor (domestic coal prices and inflation index) and one factor (only inflation index) regression to forecast the business-as-usual costs.

Among the three estimates, the one factor (inflation index) regression based estimate has the least growth and is therefore the most competitive, so we have used that as our benchmark against which to compare decarbonization costs.

We found that the cost of the business-as-usual pathway of traction will likely grow at an annual rate of at least 3.8% from INR 4.03/kWh in 2013 to INR 7.93/ kWh by 2030.

5.3 Estimation of optimal power generation capacity

To estimate the wind and solar power generation capacity required to meet a given demand, we needed to estimate the typical wind and solar generation profiles in the state of Madhya Pradesh or for states closer to Madhya Pradesh. We have used the following assumptions:

Generation profile: We have used hourly generation data of Maharashtra and Gujarat (sourced from their respective load dispatch centers), as the hourly generation data for Madhya Pradesh (MP) was not available. These states were chosen because of their proximity to MP and availability of data. We note that there could be some differences in the profiles between these states and MP. However, IR need not generate all the electricity it needs in MP in that state itself. It could generate renewable power in states that have good wind and solar resources and wheel the power to MP.

Electricity demand forecast: Indian Railways has asked us to assume a flat demand load curve of 200 MWh for the present and assume that the demand will grow at a CAGR of 6% moving forward based on the assumptions used in the Phase 1 (CPI, 2016) of the study. We estimated the demand for 2022 and 2030 based on the given annual growth rate.

Cost optimization: Our optimization problem is to meet electricity demand of IR at all times (during a 24-hour period) using solar and wind power and balancing options with the condition that IR stays carbon neutral on net energy basis.

Our **objective** is to minimize the cost of running a 100% decarbonized energy system for Indian Railways.

$$Minimize, Total\ cost = \sum_{i=1}^{24} \left\{ \sum_{j=1}^{J} C_{Gj} * U_{Gji} + \sum_{k=1}^{K} C_{Bk} * U_{Bki} \right\}$$

Where,

i = hours, 1 to 24

j = renewable energy sources, solar and wind

C_{Gj} = cost of generation from solar (s) and wind (w)

U_{Gj} = units generated from solar (s) and wind (w)

k = balancing options

C_{Bk} = cost of electricity per unit for balancing options

U_{Bkj} = units consumed from balancing options

$$U_{GSi} = (CAP_S * CUF_{Si})/1000$$

$$U_{GWi} = (CAP_W * CUF_{Wi})/1000$$

Where,

CUF_{Si} = Capacity utilization factor of solar

CUF_{Wi} = Capacity utilization factor of wind

CAP_S = Installed capacity of solar

CAP_W = Installed capacity of wind

$CAP_S \geq 0$; $CAP_W \geq 0$;

Our objective function is subjected to the following constraints:

Demand constraint: Electricity generation from renewable sources such as solar, wind power, and the balancing options should meet demand at all times during the day. At 100% decarbonization level, the demand would be met through a combination of generation from renewable sources and the balancing options. In case of decarbonization level below 100%, the combination of generation from renewable sources and the balancing options would meet a percentage of the total demand, the remaining demand would be met through grid power. The total cost in case of decarbonization level below 100% would be derived from the energy consumed from combination of generation from renewable sources, the balancing options and grid power (consumed for meeting the remaining demand).

Eq ….

For every i, $\sum_{j=1}^{J} U_{Gji} + \sum_{k=1}^{K} U_{Bki} + U_{Gri} \geq U_{Di}$

Where,

j = renewable energy sources, Wind and Solar

i = hours, 1,2,3,4,5,……….,24

k = balancing options, 1,2,3

U_{Gri} = grid energy, for 100% decarbonisation scenario, $U_{Gri} = 0$

U_{Di} = Electricity demand of Indian Railways; ≥ 0;

$$U_{Gji} = (CAP_j * CUF_{ji})/1000;\ U_{GSi} = (CAP_S * CUF_{Si})/1000;\ U_{GWi} = (CAP_W * CUF_{Wi})/1000$$

$U_{Gji} \geq 0$; U_{Bki} = Units consumed from the balancing options, balancing options include battery storage, power banking and flexible gas based power plant

The demand constraints in the optimization problem would be as below:

$$(U_{GS1} + U_{GW1} + U_{BS1} + U_{BP1} + U_{BO1}) \geq U_{D1}$$

$$(U_{GS2} + U_{GW2} + U_{BS2} + U_{BP2} + U_{BO2}) \geq U_{D2}$$

$$(U_{GS3} + U_{GW3} + U_{BS3} + U_{BP3} + U_{BO3}) \geq U_{D3}$$

....

$$(U_{GS24} + U_{GW24} + U_{BS24} + U_{BP24} + U_{BO24}) \geq U_{D24}$$

Decarbonization constraint:

For the percentage decarbonization level, the total generation from clean energy sources i.e. solar and wind should be greater than the total non-clean energy sources such as flexible gas-based balancing options. In the case of balancing with battery storage and power banking options, we are generating excess clean energy from our wind and solar sources so that we can charge the battery and the power banking to the level that is adequate enough to meet the shortfall when there is no wind and solar power generation.

$$\sum_{i=1}^{24} \sum_{j=1}^{J} U_{Gji} \geq \%\ Decarbonization\ level * (\sum_{i=1}^{24} U_{Di})$$

In cases when the percentage decarbonization level is less than 100%, the remaining demand would be met by the conventional energy drawn from the electricity grid. In our problem, we are solving the problem for 100% decarbonization level hence, we have not considered any grid component in our decarbonization constraint equations.

In cases when we are using gas as balancing option, we would need to put up excess solar and wind power capacity to offset the carbon injected into the system by units consumed from flexible gas-based power plant. The excess generation of clean energy can be sold on the power exchanges or any other third party (if allowed).

Eq ....

In cases when gas is used for balancing the demand, the decarbonization equation would be as below:

$$\sum_{i=1}^{24} \sum_{j=1}^{J} U_{Gji} \geq \%\ Decarbonisation\ level * (\sum_{i=1}^{24} U_{Di}) + \sum_{i=1}^{24} U_{BOi}$$

Here,

UB_{Oi} = Units consumed for own flexible gas-based thermal power plant

In cases when power banking is used for balancing the demand, the incoming energy from the grid would inject carbon into the system and hence, we would need to neutralize this carbon added by the units consumed from the power banking arrangement. In this case, the decarbonization equation would be as below:

$$\sum_{i=1}^{24} \sum_{j=1}^{J} U_{Gji} \geq \%\ Decarbonisation\ level * (\sum_{i=1}^{24} U_{Di}) + \sum_{i=1}^{24} U_{BPi}$$

Here,

UB_{Pi} = Units consumed from the power banking arrangement

Balancing constraint:

Balancing options will have a limitation on their capacities. For example, a battery will have a specific storage capacity, a power banking arrangement will have a limit on the maximum amount of power that can be fed into the grid and drawn from the grid, and a flexible thermal power plant will also have a limitation the maximum amount of power it can generate.

For determining the capacity of balancing options - power banking and battery storage, we have assumed a system where there is only one balancing option available. For example – for battery storage, the total excess generation should be equal to total deficit. The total deficit here is the difference between total demand and total generation from renewable generation sources. Similarly, for a power banking arrangement, the total excess generation should be equal to total deficit. In an ideal case, the capacity of balancing should have been determined based on other external constraints such as availability of investment and contractual arrangements.

Scenario 1: Balancing with Battery Storage

Here, we are considering that only one balancing option is available, that is battery storage. For balancing the system with battery storage, we denote the units consumed from battery storage and the capacity of battery storage as below:

$$\forall\, i \in \{1,2,3,4,5,\ldots\ldots,24\},\quad \forall\, k \in \{1,2,3\},\quad \forall\, m \in \{1,2,3,4,5,\ldots\ldots,23\}$$

$$-CAP_{Bk} \le \sum_{l=i}^{(i+m-1)\,MOD24} U_{Bkl} \le CAP_{Bk}\quad,\quad \sum_{l=i}^{(i+23)\,MOD24} U_{Bkl} = 0$$

$$CAP_{Bk} = capacity\ of\ balancing\ option$$

The constraint equations for balancing the demand with battery storage are as below:

$$-CAP_{BS} \le \sum_{l=i}^{(i+m-1)\,MOD24} U_{BSl} \le CAP_{BS}\ ,\quad \sum_{l=i}^{(i+23)\,MOD24} U_{BSl} = 0$$

$$CAP_{BS} = capacity\ to\ which\ battery\ can\ be\ charged\ and\ discharged$$

$$U_{BSi} = the\ units\ consumed\ from\ the\ battery\ system\ for\ balancing\ the\ demand$$

Now,

When there is a shortfall in generation from solar and wind power sources, the net load (total load – total generation from RE) would be positive as represented below:

$$\text{For every i},\ \sum_{j=1}^{J} U_{Gji} < U_{Di}$$

The battery would be discharged for meeting the total demand and balancing the system.

When there is excess generation from the solar and wind power sources, the net load would be negative as represented below:

$$\text{For every i},\ \sum_{j=1}^{J} U_{Gji} > U_{Di}$$

The battery would be charged and the total excess generation in the particular hour would get stored into the battery system.

Scenario 2: Balancing with Power Banking

For balancing with power banking option, we would use the similar methodology as used for balancing with battery storage in Scenario 1. The capacity of the power banking arrangement would be constrained by an external constraint such as the contractual arrangement on power banking between Indian Railways and other power distribution companies.

The units required for balancing here would be consumed from power banking arrangement.

The units consumed from the power banking option and the capacity of power banking arrangement is described below:

$$\forall\, i\ \in \{1,2,3,4,5, \ldots\ldots\ldots, 24\},\ \ \forall\, k\ \in \{1,2,3\},\ \ \forall\, m\ \in \{1,2,3,4,5, \ldots\ldots\ldots, 23\}$$

$$-\,CAP_{Bk} \leq \sum_{l=i}^{(i+m-1)\,MOD24} U_{Bkl} \leq CAP_{Bk} \quad , \qquad \sum_{l=i}^{(i+23)\,MOD24} U_{Bkl} = 0$$

The constraint equations for balancing the demand with battery storage are as below:

$$-\,CAP_{BP} \leq \sum_{l=i}^{(i+m-1)\,MOD24} U_{BPl} \leq CAP_{BP} \quad , \qquad \sum_{l=i}^{(i+23)\,MOD24} U_{BPl} = 0$$

$$CAP_{BP} = capacity\ of\ the\ power\ banking\ system$$

$$U_{BPi} = the\ units\ consumed\ from\ the\ power\ banking\ for\ balancing\ the\ demand$$

Now,

When there is a shortfall in generation from solar and wind power sources, the net load (total load – total generation from renewable energy) would be positive as represented below:

$$For\ every\ i, \qquad \sum_{j=1}^{J} U_{Gji} < U_{Di}$$

The optimization problem would first consume units from the cheaper balancing option. The power banking is a cheaper option here.

When there is excess generation from the solar and wind power sources, the net load would be negative as represented below:

$$For\ every\ i, \qquad \sum_{j=1}^{J} U_{Gji} > U_{Di}$$

The energy would be stored into power banking arrangement and the total excess generation in that particular hour would get stored into the power banking system.

Scenario 3: Balancing with flexible gas based generation:

For balancing with flexible gas-based power plant, balancing constraint for flexible gas would be as follows:

For every i, $\quad 0 \leq = U_{BOi} \leq CAP_{BOi}$

Here,

$$CAP_{BOi} = maximum\ contracted\ capacity\ with\ flexible\ gas\ based\ power\ plant$$

$$CAP_{BOi} = Total\ balancing\ need / PLF_{BO}$$

$$PLF_{BO} = Plant\ load\ factor\ of\ the\ flexible\ gas\ based\ plant$$

The capacity of the flexible gas based power plant would be derived using the plant load factor of the gas-based thermal power plant.

Balancing with gas based plant would inject carbon into the system and hence displace the carbon injected, we need to do excess generation so that the carbon injected into the system is neutralized and the system remains decarbonized. This excess generation from renewable sources can be exported to grid. In this case, the balancing with flexible gas based plant would operate similar to the power banking arrangement.

5.4 Estimation of balancing costs

For estimating the balancing costs, we have used the following methodology:

Power Banking: The balancing costs in this case are the power banking charges plus the cost incurred in generating the excess units that were stored in the power banking facility. From our analysis of the load curve, we found that the excess generation is largely coming from wind power generation and hence, we have used the wind power generation cost for estimating the costs incurred in generating the excess units stored in power banking arrangement. This cost has been subtracted from the cost of power generation from wind to avoid the double counting of the costs.

Gas-based power plant: In the case of balancing with flexible gas based power plant, the units required for balancing are coming from the gas based plant and hence, we have used the LCOE of the gas based plant for estimating the balancing costs. We have assumed that the excess units generated from the renewable energy sources for balancing the carbon injected into the system, would be sold on the power exchanges. This income from sale of power has been subtracted from the cost of wind power generation.

Battery: For estimating the balancing costs for battery case, we have used similar methodology as used for balancing with power banking arrangement as discussed in the first bullet point above.

5.5 Risk assessment

We identified a set of policy and regulatory risks that would likely impact the decarbonization plans of Indian Railways, through primary and secondary research. In Table 5 below, we explain these risks:

Based on our discussions and responses we received from the stakeholders, we rated the probability of these risks occurring on the scale of: Negligible: 0.1; Likely: 0.5; Near certainty: 1.0. Likewise, we rated potential impact of these risks on the cost of decarbonization (if they occur) on a scale of: Negligible: 10; Critical: 50; Catastrophic: 100. The results are presented in Table below.

Table 7: Policy/Regulatory risk definitions

RISK	DESCRIPTION
Delay in receiving approvals/permits	Construction of power plants and transmission and distribution projects would require government approvals and permits for land acquisition etc. A delay in receiving these permits would delay IR's project plans and may cause increase in costs.
Lack of or delay in building new transmission and distribution infrastructure	Lack of transmission infrastructure in areas of high wind and solar resource would mean new infrastructure has to be built. Delay in building new infrastructure may again lead to increase in costs.
Grid congestion	Congestion on inter-state and intra-state transmission networks will inhibit free flow of electricity as and when required. This may hamper the operations of IR.
Delay in introducing framework for forecasting, scheduling & imbalance handling for renewable energy	Currently, inter-state sale of renewable energy is limited due to lack of a consistent forecasting and scheduling framework. A consistent framework for both intra-state and inter-state is required for smooth flow of renewable energy.
Delay in development of balancing market	The development of a national or a regional balancing market, which contains various back-up power generation capacities, such as spinning/primary reserve capacity, secondary reserve capacity, and tertiary reserve capacity would socialize the balancing costs among various players, thereby, reducing costs of individual consumers. Also, with the development of such markets a compensation framework for flexible thermal power plants would likely be drafted, which currently does not exist. A delay in developing a national/regional balancing markets means higher costs for individual consumers as they have to develop balancing options on their own if they are adopting a high decarbonization pathway.
Delay in introduction of renewable energy trade on power exchanges	Currently, variable renewable energy such as wind and solar power cannot be traded on power exchanges as they cannot be scheduled due to lack of a standardized framework for forecasting and scheduling. Trading on power exchanges could be one of the cheapest balancing options for any consumer dealing with high share of renewable energy.
Reduction in national renewable energy targets	The Indian government has set ambitious renewable energy targets. However, if a change in government results in reduction of renewable energy targets, then the market development could be negatively impacted resulting in higher costs of decarbonization.
Hurdles in operationalizing IR's status of distribution licensee	The status of *Deemed Transmission and Distribution Licensee* of Indian Railways was clarified by the Central Electricity Regulatory Commission in November 2015. However, several states are yet to recognize this status due to their reluctance to let go of a valuable consumer, such as IR. A Licensee status will give more freedom to IR to procure power competitively rather than relying on state DISCOMS for supply of power at tariffs determined by their respective regulatory commissions. Further, freedom to choose suppliers also gives the freedom to choose the energy mix for IR.
Lack of availability of power banking	Banking of power refers to energy exchange between two interested parties with complementary energy needs. Power banking could provide a cost-effective balancing option.
Lack of availability of Open Access	Open Access regulations allow eligible (large/bulk) consumers to purchase electricity directly from power generating companies or trading licensees of their choice and correspondingly provides the freedom to generating companies to sell to any licensee or to any eligible consumer. However, some states do not encourage Open Access for the fear of losing their profitable consumers or for lack of spare transmission capacity. Lack of Open Access in any particular state will hinder IR's electricity procurement plans from their supplier of choice.

Table 8: Probability and expected impact risk scores

POLICY RISK	REMCL			MPNED			MPERC			TOTAL SCORE
	PROBABILITY	IMPACT	TOTAL	PROBABILITY	IMPACT	TOTAL	PROBABILITY	IMPACT	TOTAL	
Delay in receiving approvals/permits	0.5	50	**25**	0.1	50	**5**	0.1	50	**5**	**35**
Lack of or delay in building new transmission and distribution infrastructure	0.5	10	**5**	0.1	50	**5**	0.1	10	**1**	**11**
Grid congestion	0.1	50	**5**	0.1	100	**10**	0.1	10	**1**	**16**
Delay in introducing Framework for Forecasting, Scheduling & Imbalance Handling for Renewable Energy at Inter-state level		50	**0**	0.5	50	**25**	1	50	**50**	**75**
Delay in development of balancing market	0.5	100	**50**	0.5	50	**25**	0.5	50	**25**	**100**
Delay in introduction of renewable energy trade on power exchanges	0.1	50	**5**	0.1	50	**5**	0.1	50	**5**	**15**
Reduction in national renewable energy targets		10	**0**	0.1	10	**1**	0.1	10	**1**	**2**
Hurdles in operationalizing the status of distribution licensee	1	100	**100**	0.5	100	**50**	0.5	50	**25**	**175**
Lack of availability of power banking	0.5	100	**50**	0.5	100	**50**	0.5	100	**50**	**150**
Lack of availability of Open Access	0.5	100	**50**	0.1	100	**10**	0.1	50	**5**	**65**

6. References

BNEF, 2016; New Energy outlook 2016; https://www.bloomberg.com/news/articles/2016-06-13/batteries-storing-power-seen-as-big-as-rooftop-solar-in-12-years

BSES, 2015; Bid document for banking of power by BRPL; http://www.bsesdelhi.com/docs/pdf/Tender_for_Summer_power_import_under_banking_09.06.2015.pdf

CPI, 2016; Decarbonization of Indian Railways; https://climatepolicyinitiative.org/wp-content/uploads/2016/07/Decarbonization-of-Indian-Railways_Consultation-Draft.pdf

CERC, 2015a; Report of the Committee on Spinning Reserve; http://www.cercind.gov.in/2015/orders/Annexure-%20SpinningReseves.pdf

CERC, 2015b; Framework on Forecasting, Scheduling, and Imbalance Handling for Variable Renewable Energy Sources; http://www.cercind.gov.in/2015/regulation/SOR7.pdf

GS, 2015; Equity Research - The Great Battery Race

PIB, 2016; International Conference on Decarbonization of Indian Railways- Mission Electrification begins tomorrow; http://pib.nic.in/newsite/PrintRelease.aspx?relid=153196

IHS, 2015; Price Declines Expected to Broaden the Energy Storage Market; http://news.ihsmarkit.com/press-release/technology/price-declines-expected-broaden-energy-storage-market-ihs-says

Reuters, 2016; Battery energy storage costs seen falling 70 percent by 2030; http://in.reuters.com/article/energy-storage-idINKCN0UY00V