THE **NEW** CLIMATE **ECONOMY**

The Global Commission on the Economy and Climate

CLIMATE POLICY INITIATIVE

ICRIER

Decarbonization of Indian Railways

Charith Konda

Saurabh Trivedi

Gireesh Shrimali

January 2017

A CPI Report

Acknowledgements

We acknowledge the valuable contributions made by Sudhir Garg (Executive Director, Electrical, Ministry of Railways), Sudhir Saxena (COO, REMCL), Niraj Kumar (Director Finance, IRFC), David Nelson (Executive Director, Energy Finance, CPI), and Christoph Wolff (MD, European Climate Foundation) for this study. We also thank the Advisory Committee members – Shuba Raghavan (Lumina Decision Systems), Stephen Perkins and Lorenzo Casullo (International Transport Forum, OECD), Willy Bontinck (International Union of Railways and Belgian Railways) for their inputs.

This report has been funded by UK aid from the UK government; however the views expressed do not necessarily reflect the UK government's official policies. We extend special thanks to the UK government and the New Climate Economy for their support, and our research partner ICRIER. This paper contributed to the 2016 work programme of the New Climate Economy project which was set up to help governments, businesses and society make better-informed decisions on how to achieve economic prosperity and development while also addressing climate change. We also thank Maggie Young and Tim Varga for internal review.

Descriptors

Sector	Transportation	
Region	India	
Keywords	Decarbonization, railways, transportation, renewable energy, infrastructure	
Related CPI Reports	Better Growth, Better Climate	
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.

Contents

Executive Summary **1**

1. Introduction **4**

2. Indian Railways' energy profile **5**

2.1 Current energy consumption 5

2.2 The need for electrification 5

2.3 Growth in electricity demand 5

2.4 Clean electricity supply options 6

3. Decarbonization pathways **8**

4. Comparing the cost-effectiveness of decarbonization to business as usual **9**

4.1 Costs of the business as usual pathway 9

4.2 Comparing costs with the decarbonization pathways 9

4.3 Innovative financing to reduce decarbonization costs 12

5. Issues in implementing decarbonization **14**

5.1 State policies 14

5.2 Load balancing 16

6. Recommendations and conclusion **17**

6.1 Recommendations 17

6.2 Future work 17

7. Appendix **18**

7.1 Methodology for electricity demand forecast 18

7.2 Methodology for business-as-usual cost forecast 18

7.3 Forecast of renewable energy technology costs: 18

7.4 Estimation of decarbonization costs: 22

7.5 Status of net metering 22

7.6 Rating of balancing options 22

8. References **25**

Executive Summary

India currently stands in a moment of opportunity in which it is evident that transitioning to low-carbon systems can bring about economic growth. The falling costs of renewable energy, ambitious government plans for rapid deployment of renewable energy, and increasing financial support from international governments and investors all indicate that the transition to a low-carbon economy is not only possible, but already underway.

In accordance with the 2015 international Paris Agreement on climate change, India has pledged a reduction in emissions intensity of 33-35% by 2030 from 2005 levels. India has also set a target to transition to non-fossil fuel based energy for 40% of its cumulative electricity generation capacity by 2030. However, the work remains to figure out the practicalities of the low-carbon transition at the national, sectoral, and industrial levels. One key sector of the Indian economy that could set a strategic example for decarbonization and meeting India's 2030 targets is the rail transport system, and specifically Indian Railways (IR), India's national railway service.

IR is currently the world's second largest railway network and is the single largest consumer of electricity in India, consuming about 18 TWh per year, or roughly 2% of the country's total power generation. IR also consumes 2.6 billion liters of diesel annually, or 3.2% of the total diesel consumption of the transport sector in India. In addition, the energy demand of IR is expected to triple by 2030 to 49 TWh due to increasing passenger volume.[1]

Indian Railways is the single largest consumer of electricity in India. Prioritizing decarbonization of IR would help India achieve its carbon emissions reduction targets.

Because of the volume of IR's energy consumption, prioritizing decarbonization of Indian Railways could help India achieve its 2030 emissions reduction goals as well as improve energy security by reducing fossil fuel imports. In addition, decarbonization may be a more cost-effective option that is cheaper than the business-as-usual scenario for IR in the long run.

In this report, we have identified different potential pathways to decarbonization of IR by 2030 and examined their cost-effectiveness and feasibility.

A first and essential step to decarbonization of IR is to transition to an electrified rail network, and away from a diesel-powered rail network. As of 2015, IR used predominantly coal-based power and diesel fuel. It had electrified 38% of its track (in route kms), which carries approximately 63% of freight traffic and 50% of passenger traffic. An electrified rail network can more easily transition to clean energy alternatives such as solar and wind power, whereas there is limited availability of clean fuel alternatives. In line with this, IR already has aggressive plans for electrification.

Assuming electrification to the maximum extent possible, we have identified and examined eight possible decarbonization pathways separately for the traction segment (energy use for the railroads) and the non-traction segment (energy use for the supporting infrastructure: the stations, service buildings, street lighting, etc.) of IR. The different scenarios we considered are: captive generation (where IR builds and owns renewable energy capacity) vs. purchasing renewable energy; at a normal rate (100% decarbonization by 2030) vs. at an accelerated rate (100% decarbonization by 2020); and an all solar power pathway vs. a mix of solar and wind power.

In order for decarbonization of IR to be successful, it's necessary for the pathway to decarbonization to be both cost-effective and feasible to implement. We have examined the cost-effectiveness of each pathway, as well as potential barriers to implementation.

Solar and wind power are the most feasible clean electricity options for IR, because other renewable sources have much longer construction times. While an all-solar pathway would be cheaper in terms of pure generation costs, a mix of solar and wind would provide a more balanced generation profile, and thus lower balancing costs.[2] As we found that an all solar pathway is only 6% cheaper[3] than a mixed solar and wind pathway, and a mix of solar and wind power might have

1 This assumption is consistent with IR's own estimates.

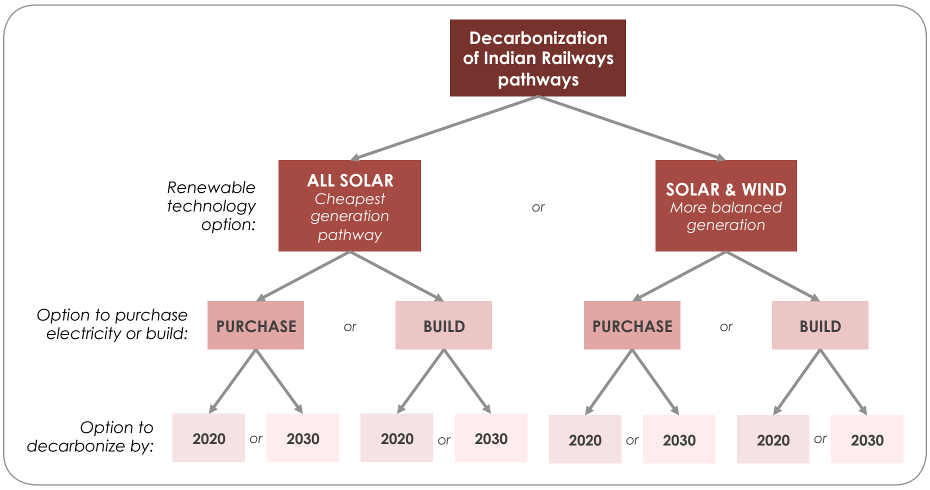
2 While solar power generation reaches its peak around noon, wind power generation typically picks up during the evening in India.

3 In terms of total (traction and non-traction) average annual cash outflows at a normal rate of decarbonization (i.e., 100% decarbonization by 2030)

lower overall costs due to lower balancing costs, we calculated the costs of each decarbonization pathway assuming a mix of solar and wind power.

In this phase of the study, which is a high-level scoping exercise, to assess cost-effectiveness, we compared the costs of each decarbonization pathway (which includes cost of generation, average transmission and distribution charges and losses, cross-subsidy charges (where applicable), and does not include balancing costs) with a business-as-usual scenario, where IR does not decarbonize at all, in both net present value terms and yearly cash outflows. We acknowledge that further work is required to estimate

Decarbonization Pathways



all the costs of decarbonization, including the need for new transmission and distribution infrastructure and balancing costs. Further, we also did not examine the effect of demand-side measures, such as energy efficiency and energy conservation.

All the components of cash flows used to compare the cost of decarbonization pathways with the business-as-usual pathway are represented in nominal terms throughout the report. As the costs of power are different for the traction and non-traction segments under the business-as-usual scenario, we analyzed the two segments separately.

For the traction segment, we found that all decarbonization pathways are more cost-effective than business-as-usual, and that the most cost-effective pathway is captive generation, at an accelerated rate of decarbonization. When we examined yearly cash outflows, we found the accelerated, captive generation pathway is not only the cheapest on average but also the least volatile;[4] it is 32% cheaper and 66% less volatile than business-as-usual. Furthermore, we found all decarbonization pathways to be at least 17% cheaper than business-as-usual. Even in net present value terms, we found all four options to at least 15% cheaper than business-as-usual, which establishes a clear case for 100% decarbonization by 2030 in order to lower costs.[5]

For the non-traction segment, we found that the decarbonization pathway of captive generation at an accelerated rate of decarbonization is even more cost-effective than in the traction segment. When we examined yearly cash outflows, we found that the accelerated, captive generation pathway is 69% cheaper than business-as-usual. Furthermore, in net present value terms, all decarbonization pathways are at least 33% cheaper than business-as-usual, with the accelerated captive generation pathway providing a 50% cost savings over business-as-usual. **Given the stronger greater potential for cost savings in the non-traction segment, we recommend that IR prioritize the decarbonization of the non-traction segment.**

Decarbonization of IR by 2030 will lower costs by at least 17% in the traction segment, and at least 33% in the non-traction segment, when compared with business as usual.

While it's evident that decarbonization of IR is more cost-effective than a business-as-usual pathway, it's also important to examine if decarbonization is feasible to implement. There are several challenges to implementation of decarbonization that will be important to address, particularly poor implementation of state policies around net metering an As d open

4 Less volatility (i.e., variation around the average) means less stress on IR finances on a year-to-year basis.

5 As the decarbonization expenditures were examined from IR's perspective, all the cash flows were discounted at 8.03%, which is IR's cost of capital.

access, and the need for low-cost and feasible balancing options for renewable energy.

State policies around net metering and open access, which facilitate load balancing and third-party power procurement, vary state by state and are often poorly implemented. This could become a significant barrier to implementation of IR's decarbonization pathway, specifically in the non-traction segment.

To manage issues around net metering policies, IR should enter into net metering arrangements with states which have already encouraged net metering, particularly Tamil Nadu, Delhi, West Bengal, and Andhra Pradesh. Similarly, to manage issues around open access policies, IR should aim to procure power from independent power producers in the states that have already successfully implemented the open access policy.

Further, 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. However, not all of the technologies available for load balancing are currently feasible for IR. We examined the different load balancing options that are or will be) available to IR and assessed their technical, regulatory, and commercial feasibility. The most feasible options of the ones that are immediately available are power banking and net metering with state DISCOMS (in certain states). Pumped hydro storage may also be feasible. In the next five years, additional feasible options for load balancing will be flexible thermal power plants,[6] grid-scale battery storage, and trading on power exchanges.

6 Flexible thermal plants can be used for balancing variable renewable energy. Businesses can sell excess renewable energy on power exchanges and use energy from flexible thermal plants during the times of shortfall, but can still achieve decarbonization targets on a net energy basis – i.e. selling more clean energy than the use of thermal energy. However, this would imply that there would be a need to generate excess clean power beyond the demand to stay net clean energy positive.

1. Introduction

As a first step on the pathway towards low-carbon economic growth, India has set ambitious targets for both reducing carbon emissions and deploying more clean energy. In accordance with the Paris Agreement, India has pledged a reduction in emissions intensity of 33-35% by 2030 from 2005 levels. India has also set a target to transition to non-fossil fuel based energy for 40% of its cumulative electricity generation capacity by 2030.

However, the practicalities of this transition toward low-carbon economic growth have yet to be detailed. One key sector of the Indian economy that could both set a strategic example for decarbonization and help make significant progress towards those targets is the rail transport system, and specifically Indian Railways (IR), India's national railway service.

IR is the world's second largest rail network and India's single largest electricity consumer. Decarbonizing Indian Railways would help India achieve its carbon emissions reduction target as well as improve energy security by reducing fossil fuel imports and increasing renewable energy capacity. In addition, decarbonization may also be cost-effective in the long run due to the falling costs of renewable energy and rising costs of fossil fuel-based power.

A prerequisite to decarbonization is electrification is to transition to an electrified rail network, and away from a diesel-powered network. An electrified rail network can more easily transition to clean energy alternatives such as solar and wind power, whereas there is limited availability of clean fuel alternatives.

A complete (100%) decarbonization of Indian Railways' electricity consumption by 2030 will likely result in the following benefits:

- CO_2 cumulative emissions reduction of 45 million tons
- SO_2 cumulative emissions reduction of 150 million tons
- NO cumulative emissions reduction of 210 million tons

In addition, if IR decarbonizes at an accelerated rate, aiming for 100% decarbonization by 2020, then the required amount of additional renewable energy capacity could help achieve approximately 10% of the government's target of 160 GW of solar and wind power by 2022.

In order for decarbonization of IR to be successful, it's necessary for the pathway to decarbonization to be both cost-effective and feasible to implement. In this report, we've identified eight possible pathways to decarbonization of IR, and assessed their cost-effectiveness and feasibility in order to determine the most suitable pathway. In order to determine cost-effectiveness, we compared the costs of each pathway with a business-as-usual, no decarbonization scenario. In order to determine feasibility, we identified and examined some of the policy challenges and barriers to implementation that IR could face during decarbonization, and offer recommendations.

However, this report is a high-level scoping exercise, which is the first part of a planned three-part study to scope, plan, and implement the decarbonization of IR. In this first report, we assess the decarbonization options available to IR (from the supply side) and estimate the direct costs associated with the options identified. We included the cost of renewable electricity (levelized cost of energy (LCOE)), the average transmission and distribution charges and losses, and regulatory costs (such as cross-subsidy charges), where applicable, as part of the direct costs. The LCOE of renewable power will be different if IR generates its own power and if it procures from third party/independent power producers (IPPs) due to the difference in their cost of capital or discount rate. We used 8.03% and 10.7% as the discount rate for IR and IPPs respectively.

We did not include the cost of electrification in the costs of decarbonization because IR is planning to electrify 90% of its tracks, which will be more than 90% in traffic terms, in the next five years, to 2020-21, regardless of any decarbonization plans (PIB, 2016). As the costs of electrification will be a common cost for both business-as-usual and decarbonization pathways we did not include it in this analysis. This study does not include the capital expenditure that may be required for constructing new transmission and distribution lines and balancing costs that will be incurred in managing the variable renewable energy. The need for new transmission lines can be assessed further in a more in-depth study, through which the actual location of the renewable plants will be known. Likewise, balancing costs could be reasonably estimated at a regional level based on location of the plants and balancing options available in that particular region.

We also note that decarbonization could include demand-side management, such as energy efficiency and conservation. In this report, while we have focused only on the supply-side measures for decarbonization of IR, this would represent a worst-case for decarbonization in terms of cost-effectiveness as any demand-side measure will be most likely cheaper than supply-side measures.

This report is structured as follows: in Section 2, we discuss prerequisites to decarbonization, forecast the growth in electricity demand for IR, and assess the availability of clean energy alternatives, in order to design various decarbonization pathways for IR. In Section 3, we identify and discuss the eight decarbonization pathways that IR could pursue to achieve the goal of 100% decarbonization. In Section 4, we assess the cost-effectiveness of the different decarbonization pathways when compared with business as usual. In Section 5, we examine issues around implementation of decarbonization and recommend solutions. And in Section 6, we lay out our recommendations for IR on the best pathway to decarbonization and indicate areas for future work.

2. Indian Railways' energy profile

2.1 Current energy consumption

Indian Railways is currently the world's second largest railway network (under single management), with a network length of 66,000 route kilometers and 7,200 stations carrying 23 million passengers per day (UNDP, 2015; Business Standard, 2015a). This large network of IR includes stations, factories/workshops, offices, and housing for the staff, which are all dependent on the consumption of energy.

Indian Railways' energy consumption is divided into two segments – traction and non-traction. The traction segment consumes energy for running the network of trains and uses both electricity and diesel. The non-traction segment's energy consumption includes energy consumption at service buildings, stations, factories/workshops, street lighting, water pumping installations, and staff housing.

IR is the single largest consumer of electricity in India, consuming about 18 TWh per year, or roughly 2% of the country's total power generation, with a peak demand of about 4,000 MW. Of total electricity consumption, currently traction accounts for 85%, while non-traction accounts for the remaining 15%. IR also consumes 2.6 billion liters of diesel annually, or 3.2% of the total diesel consumption of the transport sector in India. IR spent approximately INR 29,500 crore in 2013-14 on energy bills, of which 40% was for electricity.

2.2 The need for electrification

A prerequisite step to the decarbonization of IR is to transition toward an electrified railway network and reduce the use of diesel-powered trains to the maximum extent possible. As of 2015, IR used predominantly coal-based power and diesel fuel. It had electrified 38% of its track (in route kms), carrying approximately 63% of freight traffic and 50% of passenger traffic (Business Standard, 2015b).

Electrification is a necessity for decarbonization because an electrified rail network can more easily transition to clean energy alternatives such as solar and wind power, whereas there is limited availability of clean fuel alternatives.

Electrification is a prerequisite to decarbonization because an electrified rail network can more easily transition to clean energy alternatives such as solar and wind power, whereas there is limited availability of clean fuel alternatives.

The current clean fuel alternatives include biodiesel fuel and natural gas (CNG/LNG). IR already has a target to switch to biodiesel for up to 5% of total diesel consumption (IR Budget 2014-15). However, the biodiesel market is at a very early stage in India and is fraught with many challenges, resulting in supply shortages in the open market. Due to these supply shortages, IR is facing difficulties in procuring enough biodiesel to meet its target. It is very unlikely that IR will be able to meet a major portion of its diesel consumption through biodiesel in the future.

In addition, CNG/LNG options for railways are still in demonstration stages and are very unlikely to become commercial technologies in the near future. Given the limited availability of clean fuel alternatives, along with the wide availability of clean electricity options (discussed in Section 2.4), we recommend that IR electrify its railway network to the maximum extent possible, as a prerequisite step to decarbonization.

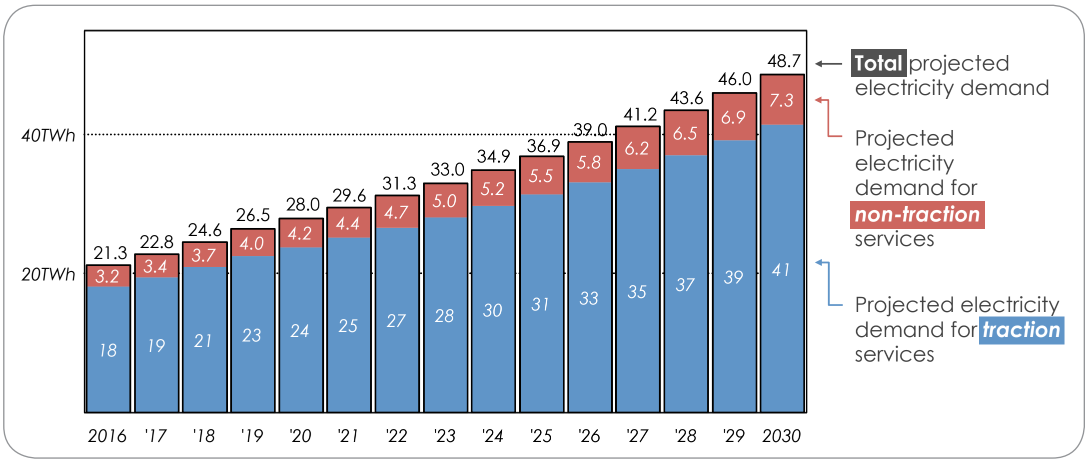
In line with this, IR already has plans for increasing electrification. IR has set an aggressive target to electrify approximately 2,000 route kms on average per year going forward from 2016. In previous years (2009 to 2015), the average yearly electrification was 850 route kms. In fact, along with the Ministry of Power, IR is further planning to electrify 35,000 route kms in the next three years to save around INR 16,000 crores of foreign exchange a year on fuel imports (Economic Times, 2016).

2.3 Growth in electricity demand

We expect the electricity demand of IR to grow at an annual rate of 6% from 21.3 TWh in 2016 to reach 48.7 TWh by 2030 (Figure 1).[7] This growth will be primarily driven by traction electricity demand due to growing passenger and freight traffic and increasing electrification of routes.

7 We discuss our methodology for electricity demand forecast in Appendix 7.1.

Figure 1: Indian Railways electricity demand forecast (TWh), 2016-2030



Source: IR Yearbook, KPMG, CPI Analysis

Passenger demand of IR will likely grow at an annual rate of 8.9% from 1,047 billion passenger kilometers in 2012 to 5,765 billion kilometers in 2032. Freight demand of IR will likely grow at an annual rate of 9.7% from 2,053 billion net ton kilometers (NTKM) in 2012 to 13,118 billion NTKM by 2032 (NTDPC, 2013). Non-traction electricity demand growth will be driven by a growing number of stations and other buildings and factories to service growing traffic.

Our research partner, ICRIER in their study (ICRIER, 2016), estimated IR's electricity demand growth in three different scenarios: optimistic, realistic, and pessimistic. According to the ICRIER study, electricity demand is expected to grow from 21 TWh in 2016 to 225 TWh, 176 TWh, and 136 TWh by 2030, under the optimistic, realistic, and pessimistic scenarios respectively.[8] Given the differences in the demand forecasts, we checked if our results would change if demand grows at a much higher rate than we forecasted. We discuss our results in Section 4.

2.4 Clean electricity supply options

The options for clean electricity alternatives that IR could transition to include solar power, wind power, nuclear power, hydropower, biomass energy, and geothermal energy. Of these, the most feasible are solar power and wind power.

For captive generation, where IR would build and own renewable energy capacity, solar and wind power might be the only two technologies that are feasible. This is largely due to the long construction times of the other technologies such as nuclear power and hydropower, which could double the typical construction time in the case of nuclear power and triple it in the case of hydropower (Table 1). The delays in construction are largely due to long clearance and approval procedures, environmental concerns, and varying state policies around royalty power[9] and land acquisition (PWC, 2014; The Wire, 2015). Timely construction of power plants will be essential for IR to meet its planned decarbonization targets cost-effectively.

Solar power and wind power are the most feasible clean electricity supply options for Indian Railways.

IR also has the option to purchase renewable energy instead of building capacity on its own, and in this case as well, solar and wind power are likely the only feasible technologies. This is because even if IR chooses to purchase power, the capacity required to meet this demand has to be newly built by power producers. More than 90% of the power generated in India (conventional power and renewable energy combined) is already being sold under power purchase agreements and IR may find it difficult to find unallocated clean power.[10]

Biomass power in India is mostly based on waste from agricultural produce, which is available only for 2-3

8 These demand forecasts are 2.8-4.6 times higher compared with our estimate of 48.7 TWh by 2030 (Figure 1). In our discussions with IR officials, we found that an electricity demand forecast of 48.7 TWh by 2030 is in line with their own estimates. Given that our estimates are in line with historical growth as well as in agreement with IR's own estimates, we considered our demand forecast numbers for the decarbonization analysis in this study.

9 Royalty power is a mandatory portion of free supply of power to the state in which the project is located.

10 IR has recently signed power purchase agreements for 50 MW from Damodar Valley Corporation and another 300 MW from Ratnagiri Gas and Power Project (Dabhol). The scope of finding non-contracted clean power sources should be further investigated.

months after harvesting (BioEnergy Consult, 2015). Further, the feedstock supply chain is not well-established, leading to supply shortages and large price fluctuations that make running of biomass power plants unviable (Biopower, Jan-Mar 2014).

India currently does not have any operational geothermal power plants and the policy detailing the target of achieving 10 GW of geothermal power capacity by 2030 is still in the draft stages (EAI, 2014; CleanTechnica, 2016). IR will not likely have access to a commercially run geothermal power plant in the foreseeable future.

Table 1: Construction times and delays of clean power plants in India

RENEWABLE ENERGY TECHNOLOGY	MINIMUM CONSTRUCTION TIME (MONTHS)	AVERAGE DELAYS RECORDED (MONTHS)
Solar power	9-12	None on producer's own land; on other land depends on state (~2-4 months)
Wind power	12-18	None on producer's own land; on other land depends on state
Hydropower	~54	96
Nuclear power	~60	60

Source: MNRE, MoP, PWC, The Wire, CRISIL

3. Decarbonization pathways

We have identified eight different pathways that IR could pursue to achieve 100% decarbonization (Figure 2), based on decisions between: captive generation (where IR builds and owns renewable energy capacity) vs. purchasing renewable energy; at a normal rate (100% decarbonization by 2030) vs. at an accelerated rate (100% decarbonization by 2020); and an all solar power pathway vs. a mix of solar and wind power.

Captive generation vs. purchasing power

To decarbonize, IR has to either set up its own renewable power generation plants, called captive power generation, or purchase power directly from renewable power producers. While there are different models for captive generation,[11] the fundamental difference between captive generation and purchasing power in our analysis is the requirement of capital investments for captive generation.

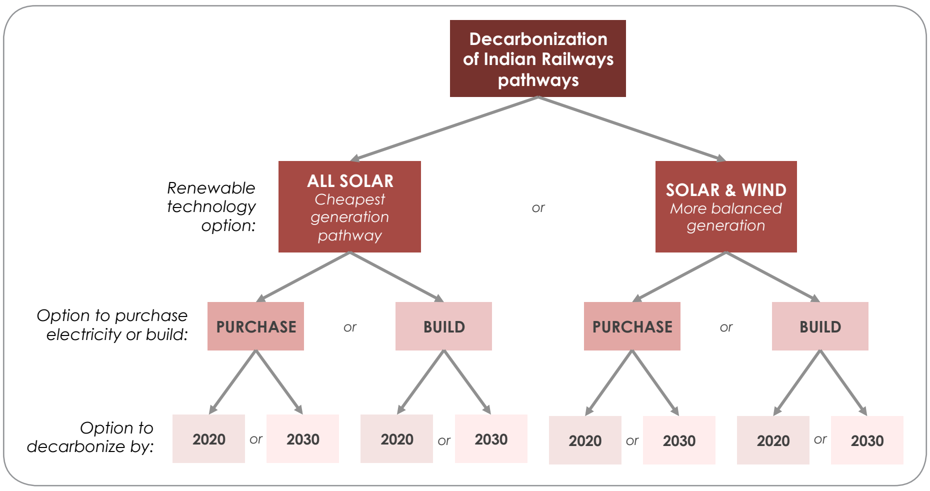
Normal vs. accelerated rate of decarbonization

The normal rate of decarbonization would be 100% decarbonization by 2030, in line with India's 2030 carbon emissions reduction target. However, given that renewable energy costs per kWh are already getting closer to some of conventional power costs per kWh, we have also considered an accelerated decarbonization pathway, in which IR would reach 100% decarbonization by 2020 instead of 2030. We assumed that IR would maintain 100% decarbonization after 2020 and 2030 under both the accelerated and normal rate of decarbonization scenarios.

All solar vs. solar and wind

We also considered an all solar pathway vs. a mix of solar and wind. An all solar pathway would be cheaper in terms of pure generation costs. However, because peak generation times differ between solar and wind power,[12] a mix of solar and wind would provide a more balanced generation profile and thus lower balancing costs. As we found that an all solar pathway is only 6% cheaper[13] than a mixed solar and wind pathway, and a mix of solar and wind power might have lower overall costs due to lower balancing costs, we have shown only the mixed pathway costs for our analysis of the cost-effectiveness of the decarbonization pathways.

Figure 2: Decarbonization pathways



11 For example, IR need not necessarily invest as well as operate the plants under a captive generation model. It could invest in a plant operated by another entity.

12 While solar power generation reaches its peak around noon, wind power generation typically picks up during the evening in India.

13 In terms of total (traction and non-traction) average annual cash outflows at a normal rate of decarbonization (i.e., 100% decarbonization by 2030)

4. Comparing the cost-effectiveness of decarbonization to business as usual

In order for decarbonization of IR to be successful, it's necessary for the pathway to decarbonization to be cost-effective.

In order to determine cost-effectiveness, we compared the costs and savings of each decarbonization pathway with a business-as-usual, no decarbonization pathway. We have also indicated the potential to further reduce decarbonization costs through innovative financing. The cost of the business-as-usual pathway of IR is discussed in Section 4.1 and the costs of the decarbonization pathways are discussed in Section 4.2. All the components of cash flows used to compare the cost of decarbonization pathways and the business-as-usual pathway are represented in nominal terms throughout the report.

We also have examined several innovative financing solutions, which could further reduce the costs of decarbonization, discussed in Section 4.3.

4.1 Costs of the business-as-usual pathway

The business-as-usual pathway is what IR will likely follow to 2030 if it chooses not to decarbonize. Up until November 2015, IR purchased power from DISCOMs, India's public electricity distribution companies, and paid a special railway tariff for the traction segment and commercial tariffs for the non-traction segment. In November 2015, the Central Electricity Regulatory Commission changed the status of IR to a deemed transmission and distribution licensee at the request of IR (CERC, 2015).[14] This meant that going forward, IR could purchase electricity directly from power producers at a mutually agreed price and transmit the electricity using its own transmission and distribution lines for the traction segment.

For the non-traction segment, IR will most likely continue as a consumer of DISCOMs. Considering IR's two different electricity procurement models for its traction and non-traction segments, we've identified separate business-as-usual pathways for each segment.

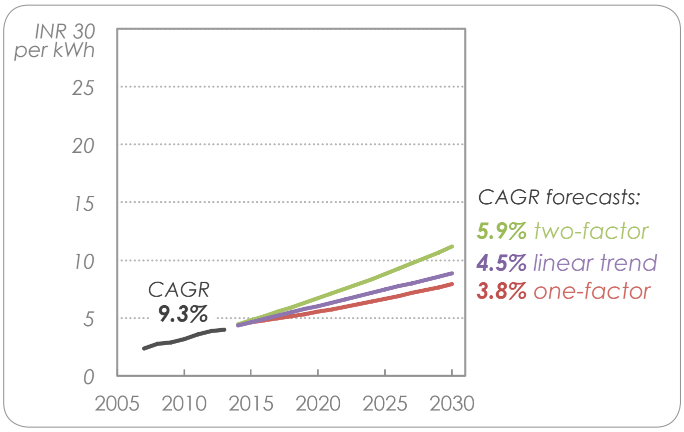
BUSINESS-AS-USUAL PATHWAY FOR THE TRACTION SEGMENT

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 the historical growth rate and two different regression-based forecast methodologies, which produced three different estimates. This is further explained in Appendix 7.2. 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 (Figure 3).

Figure 3: Forecasted cost of the business-as-usual pathway for the traction segment (INR/kWh), 2014-2030



Source: IndiaStat, NITI Aayog, CPI Analysis

14 IR petitioned for a status change to a deemed transmission and distribution licensee in order to avoid high tariffs levied by state DISCOMs and save energy costs.

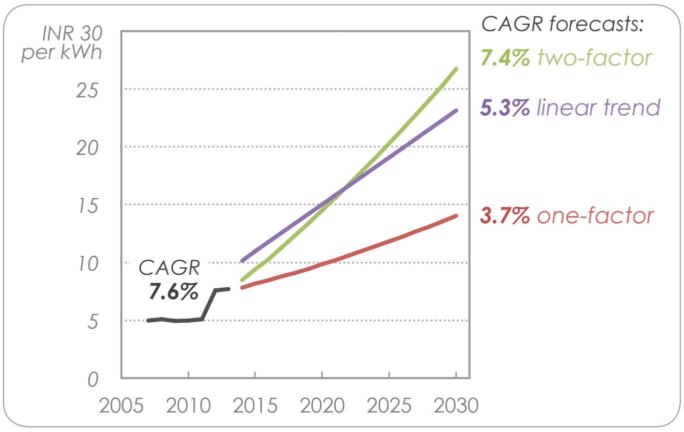
Table 2: Key assumptions for estimating decarbonization costs

CAPTIVE GENERATION	PURCHASED POWER
• Electricity generated and 100% owned by IR • Expected return on equity: 14% • Cost of debt: 8.28%; tenor: 12 years • Plant life: 25 years • No land constraint (land costs included) • Average mix of wind and solar at a ratio of 47:53	• Electricity purchased from IPPs • Expected return on equity of an IPP: 16% • Cost of debt: 12.76%; tenor: 12 years • All long-term contracts of 25 years

BUSINESS-AS-USUAL PATHWAY FOR THE NON-TRACTION SEGMENT

We defined the business-as-usual cost for the non-traction segment of IR as the average commercial tariffs of DISCOMs in India. IR already pays and will continue to pay this commercial tariff to DISCOMs for electricity consumed by the non-traction segment. In order to forecast the average commercial tariffs to 2030, we

Figure 4: Forecasted cost of the business-as-usual pathway for the non-traction segment (INR/kWh), 2014-2030



Source: IndiaStat, NITI Aayog, CPI Analysis

followed an approach similar to the one we used to forecast the traction business-as-usual costs, explained in Appendix 7.2. We considered the estimate with the least growth in this case as well.

We found that the cost of the business-as-usual pathway for the non-traction segment will likely grow at an annual rate of at least 3.7% from INR 7.70/kWh in 2013 to INR 14.03/kWh by 2030 (Figure 4).

4.2 Comparing costs with the decarbonization pathways

Because the business-as-usual pathways are different for the traction and non-traction segments, we have also estimated the costs of decarbonization separately for the traction and non-traction segments.

In order to estimate the costs of each decarbonization pathway, we forecasted the levelized cost of electricity for wind and solar power (see Appendix 7.3) and used the assumptions listed in Table 2. We used the landed cost of renewable energy (LCOP) to estimate the decarbonization costs, which includes the levelized cost of electricity plus transmission and distribution costs (not applicable to rooftop solar) plus a cross-subsidy surcharge for ground-mounted projects in the non-traction segment. Hence, our estimate of decarbonization costs includes all costs, except the cost of balancing. Balancing costs can be accurately estimated when examined at a regional level. As the decarbonization expenditures were examined from IR's perspective, all the cash flows were discounted at 8.03%, which is IR's cost of capital. A more detailed methodology is provided in Appendix 7.4.

We present a comparison of decarbonization costs of the four pathways: captive generation vs. purchases; and an accelerated rate of decarbonization vs. normal rate – all using a mix of solar and wind power.

THE TRACTION SEGMENT

In comparing costs, we found that all decarbonization pathways in the traction segment would be cheaper than the business-as-usual pathway in terms of both net present value (NPV), which would be 15-19% cheaper, and average annual cash outflows, which would be 17-32% cheaper.

Of the four decarbonization pathways under the solar and wind mix pathway, the most cost-effective is captive generation under an accelerated rate of decarbonization, with 32% savings in annual average cash outflows compared with business-as-usual cash outflows of INR 27,145 crores during 2016-40 (Table 3).

Figure 5: Annual cash outflows for the traction segment in two scenarios: Captive generation vs. purchased power

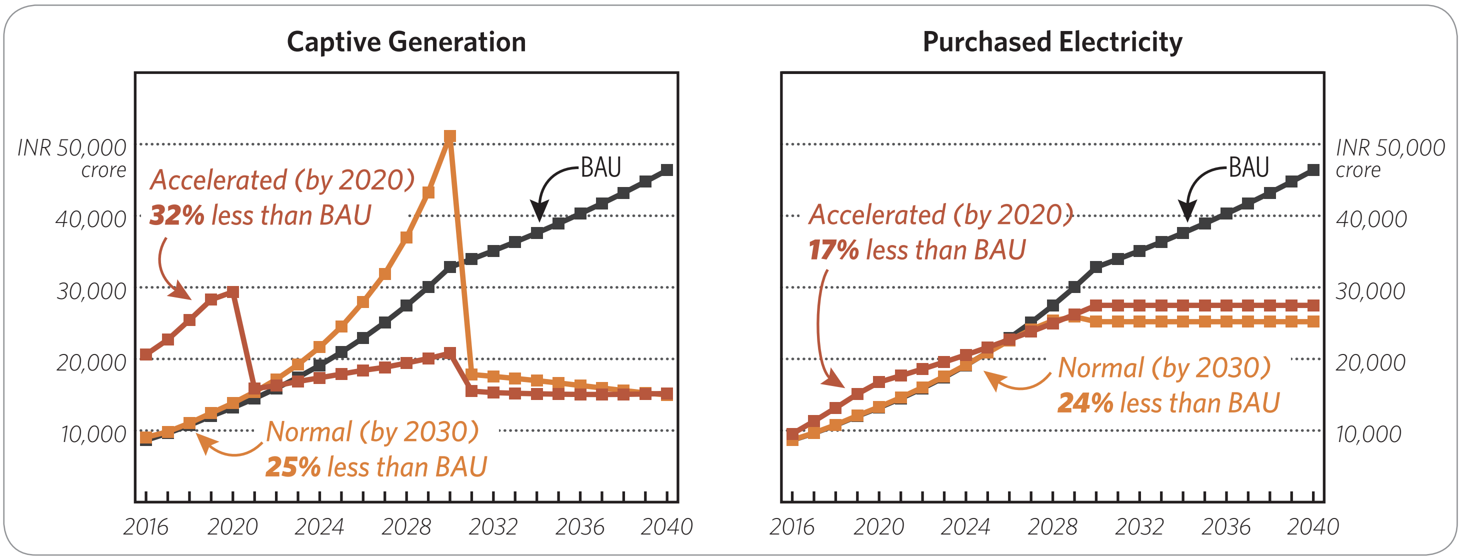


Table 3: Savings in average annual cash outflows and variations for the traction segment

SAVINGS IN AVERAGE ANNUAL CASH OUTFLOWS COMPARED WITH BUSINESS-AS-USUAL		
	Accelerated Rate of Decarbonization (100% by 2020)	Normal Rate of Decarbonization (100% by 2030)
Captive generation	**32%**	**25%**
Purchased power	**17%**	**24%**
Business-as-usual	INR 27,145 crores	
REDUCTION IN VARIATION OF ANNUAL CASH OUTFLOWS		
Captive generation	**66%**	**16%**
Purchased power	**53%**	**52%**
Business-as-usual	INR 12,088 crores	

We also found that variations in cash outflows in accelerated captive generation will be 66% lower compared with the business-as-usual cash outflows of INR 12,088 crores. Pathways with lower variations in cash outflows will be easier for IR to manage.

Accelerated, captive generation will likely be the most cost-effective decarbonization pathway for the traction segment, with 32% savings in annual average cash outflows compared with business-as-usual.

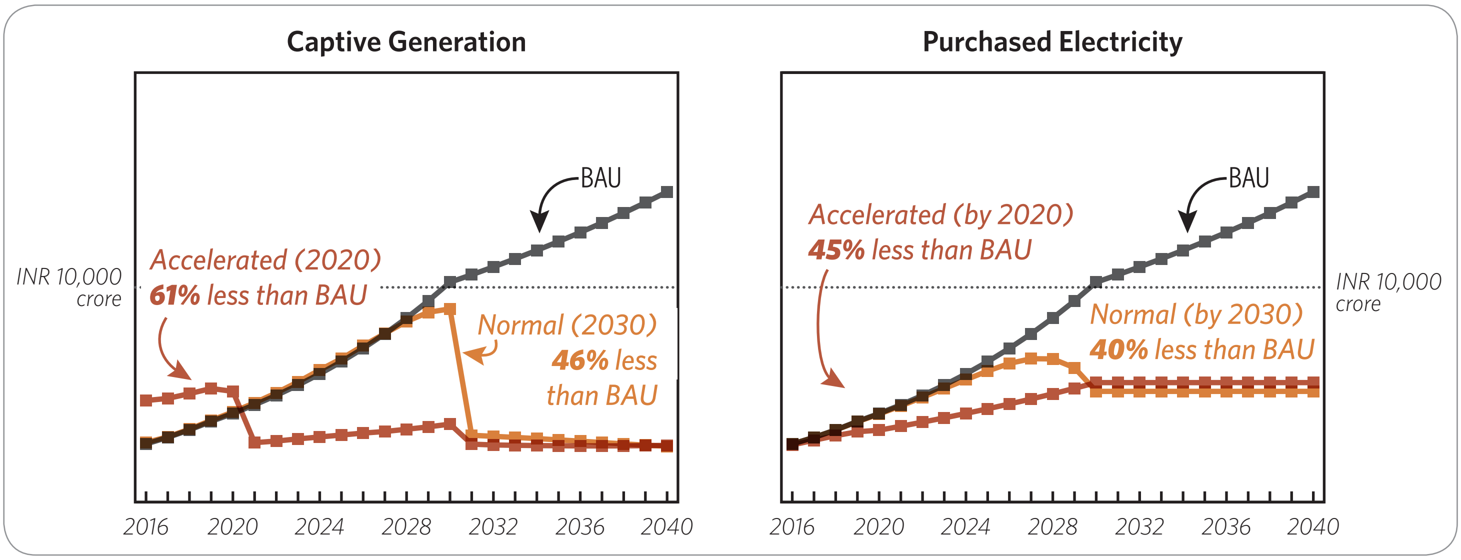
Under a pathway of accelerated captive generation, IR will have to spend 133% (INR 72,175 crores) more in the initial years (2016-2020) compared with business-as-usual. However, in the long run (2016-2040) IR will be spending 32% (INR 218,847 crores) less than business-as-usual (Figure 5).

Under normal rate captive generation, IR will have to spend 23% (INR 64,969 crores) more during 2016-30 compared with business-as-usual. However, during 2016-40, IR will be spending 25% (INR 168,935 crores) less than business-as-usual. The cost difference between the accelerated and normal rates is largely due to an additional spending of INR 170,694 crores on conventional power with the normal rate.

If the upfront capital investment required for setting up captive generation is not possible for IR, the second most cost-effective option is purchasing power at a normal rate, which will likely result in 24% savings in average annual cash outflows.

We tested these results with ICRIER's demand forecasts as well and found that results are similar. Even at higher

Figure 6: Annual cash outflows for the non-traction segment in two scenarios: Captive generation vs. purchased power



electricity demand volumes, captive generation under an accelerated rate of decarbonization continues to be the most cost-effective pathway. This is because an increase in demand will affect both the business-as-usual and decarbonization pathways in a similar way – i.e. IR has to procure electricity to meet the increased demand for both the business-as-usual pathway and one of the decarbonization pathways.

THE NON-TRACTION SEGMENT

For the non-traction segment, we found that all decarbonization pathways would be cheaper than the business-as-usual pathway in terms of both net present value (NPV) (33-50% cheaper) and average annual cash flow (40-61% cheaper). This is largely due to expected increases in the commercial tariffs IR will pay to DISCOMs for power under the business-as-usual pathway.

Of the decarbonization pathways, accelerated captive generation will likely be the most cost-effective pathway, with 61% savings in annual average cash outflows compared with the business-as-usual cash outflows of INR 8,470 crores during 2016-40 (Table 4).

Also, variations in cash outflows in captive generation in the accelerated decarbonization pathway will be 76% lower than the variations in business-as-usual cash outflows at INR 3,762 crores.

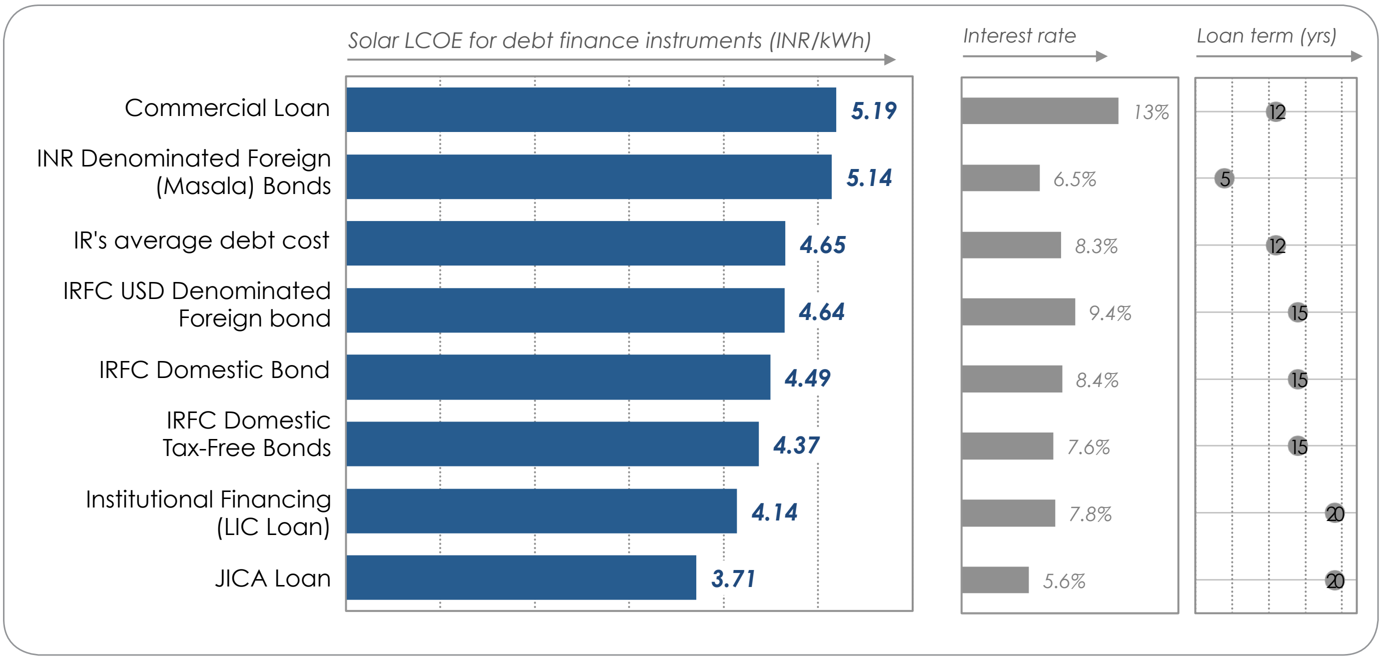
Captive generation at an accelerated rate is expected to have much higher savings than at a normal rate because a normal rate would entail purchasing power from DISCOMs at expensive commercial tariff rates for a longer period. Captive generation is also cheaper than purchasing power from third parties due the levying of cross-subsidy surcharges[15] on third party purchases in the non-traction segment.

Table 4: Savings in average annual cash outflows and variations for the non-traction segment

SAVINGS IN AVERAGE ANNUAL CASH OUTFLOWS COMPARED WITH BUSINESS-AS-USUAL		
	Accelerated Rate of Decarbonization (100% by 2020)	Normal Rate of Decarbonization (100% by 2030)
Captive generation	**61%**	**46%**
Purchased power	**45%**	**40%**
Business-as-usual	INR 8,470 crores	
REDUCTION IN VARIATION OF ANNUAL CASH OUTFLOWS		
Captive generation	**76%**	**43%**
Purchased power	**73%**	**73%**
Business-as-usual	INR 3,762 crores	

15 Typically in India electricity is subsidized for households and agriculture and these subsidies are recouped from industrial and commercial consumers in the form of cross subsidy surcharges.

Figure 7: Debt finance instruments and their impact on the LCOE for solar power



Accelerated, captive generation would be the most cost-effective decarbonization pathway for the non-traction segment, with 61% savings in annual average cash outflows compared with business-as-usual.

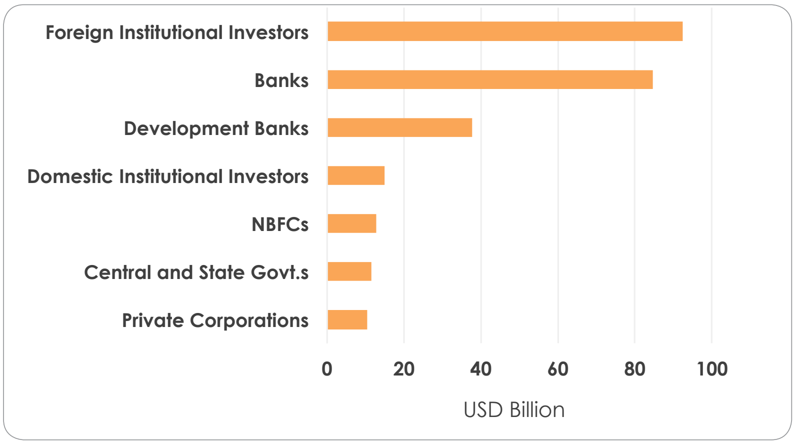
With accelerated captive generation, IR will have to spend 48% (INR 8,088 crores) more in the initial years (2016-2020) compared with business-as-usual. However, in the long run (2016-2040) IR will be spending 61% (INR 128,555 crores) less than business-as-usual (Figure 6). With captive generation at a normal rate, IR will have to spend almost the same amount as business-as-usual during 2016-2030. However, in the long run (2016-2040), IR will be spending 46% (INR 96,373 crores) less than business-as-usual. The difference in costs between the accelerated and normal rates is largely due to an additional spending of INR 53,340 on conventional power with the normal rate.

The business case for a complete decarbonization is much stronger for the non-traction segment as the savings of 61%, are much higher than the savings of 32% in the traction segment, in terms of average annual cash flows.

4.3 Innovative financing to reduce decarbonization costs

There is potential to further reduce the costs of decarbonization through innovative financing. The LCOE for solar power is sensitive to the cost and tenor of debt financing, and by tapping into sources that can provide lower cost, longer term debt, IR can reduce its decarbonization costs.

Figure 8: Maximum debt investment potential by source, 2016-2022



We have estimated the costs of decarbonization at the IR's cost of debt (8.28% for 12 years) for captive generation, and at the independent power producer's cost of debt (12.76% for 12 years) for purchased power. IR could further reduce these costs by up to 20% by funding renewable energy projects through sources that provide low-cost, long-term debt, such as Japan

International Cooperation Agency (JICA) and Life Insurance Corporation (LIC).[16] For example, if IR were to use a JICA loan at 5.6% (including currency hedging) for 20 years, that could lower the cost of solar power from INR 4.65/kWh to INR 3.71/kWh (Figure 7).

In CPI (2016), we have estimated the maximum potential of various debt investors, some of whom, such as domestic institutional investors and development banks, could provide cheaper, longer-term debt to IR. These sources could provide additional capital to IR's decarbonization efforts, beyond the capital provided by traditional sources such as commercial banks.

In total, domestic banks, domestic institutional investors, development banks, and non-banking financial companies (NBFCs) have the potential to invest USD $191.5 billion (high-end estimate) in renewable energy projects during 2016-22.

16 The cost of capital or the discount rates for the corresponding interest rates mentioned in Figure 7 ranges from 6.79% to 10.21% as compared to the discount rate of 8.03% used in the analysis elsewhere.

5. Issues in implementing decarbonization

While it is evident that decarbonization of IR is more cost-effective than a business-as-usual pathway, it's also important to examine if decarbonization is feasible to implement.

There are several challenges to implementation of decarbonization that will be important to address. In this section, we assess the significance of these challenges and propose solutions to manage them.

The feasibility of implementing the decarbonization of IR will largely depend on two key issues:

- *State policies:* Poor implementation of state policies, specifically policies governing net metering and open access, will directly affect the implementation of decarbonization initiatives of IR, especially in the non-traction segment. We examine the variation in implementation of these state policies and the implications in Section 5.1 below.
- *Load balancing:* 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. However, not all of the technologies available for load balancing are currently feasible for IR. We have assessed their technical, regulatory, and commercial (cost) feasibility to determine which are the most feasible for IR in Section 5.2.

In addition to these challenges, our discussions with IR officials also revealed that IR would need to build certain internal capabilities in order to decarbonize successfully. These capabilities include load forecasting, renewable power management, and power trading techniques. These are not discussed further in this paper but are important to note.

5.1 State policies

Poor implementation of state policies that govern net metering and open access will primarily affect IR's decarbonization efforts in the non-traction segment because IR will continue to interact with state electricity grids with the status of a consumer.[17] This is unlike the situation in the traction segment, where it would interact with other state grids with the status of a transmission and distribution licensee.

17 Even if IR opts for captive generation, it would most likely interact with state electricity grids either for load balancing purpose or for transmitting power from remote locations.

NET METERING

Net metering is an arrangement between the electricity system owner and a DISCOM, which allows the system owner to sell electricity to the DISCOM during times of surplus and draw electricity from the grid during times of deficit at predetermined prices. This mechanism is especially useful for a solar rooftop system owner for balancing electricity load and achieving carbon neutrality. However, this mechanism is not uniformly implemented across all the states in India. Hence, in order to implement decarbonization, IR will need to devise a state-by-state strategy for its rooftop solar installations, which can benefit from net metering. **By focusing on developing rooftop solar installations in states, which already have well-implemented net metering policies, IR can more quickly and feasibly implement a decarbonization plan.**

We have examined the net metering policies and implementation of the different states, and have ranked the states based on the quality of their net metering implementation.

Although 24 states in India have net metering policies, reports indicate that adoption of net metering has only been successful in six states so far (Appendix 7.5). This is largely due to structural challenges in the Indian power sector, such as:

- States in India would like to buy and sell electricity at the same prices under net metering. However, as residential and agricultural prices are artificially kept low due to political reasons, some net metering customers have to sell electricity at a loss.
- DISCOMs are not encouraging commercial and industrial consumers to opt for net metering, as this segment of consumers are the most profitable consumers for DISCOMs. States usually subsidize residential and agricultural consumers and recover part of these subsidies by levying higher tariffs on commercial and industrial consumers.[18]
- Components such as the inverters, transformers, and the overall electricity grid have to be upgraded to be able to absorb large quantities of distributed solar energy generation.

18 The uptake of solar rooftop installations driven by net metering in the commercial and industrial segments may also be slow due to lack of confidence among these consumers on receiving payments from the financially sick DISCOMs.

Table 5: Status of net metering implementation and IR's rooftop solar potential by state, 2016

STATES	NET METERING STATUS	IR'S SUITABLE ROOFTOP SPACE (SQ. FEET '000)
Stage 1		
Tamil Nadu	Operational	2,713
Delhi	Operational	1,255
West Bengal	Operational	916
Andhra Pradesh	Operational	889
Stage 2		
Uttar Pradesh	Notified	3,693
Maharashtra	Notified	2,196
Punjab	Notified	1,112
Madhya Pradesh	Notified	999
Telangana	Notified	844
Later		
Gujarat	Draft stage	3,077
Total rooftop space (Sq. feet '000)		**17,694**
Total rooftop solar power generation potential (TWh)		**0.29**

Sources: Bridge to India, Intersolar, MNRE, Bijili Bachao, CleanTechnica, Respective state electricity regulatory commissions, Indian Railways, CPI analysis

In addition to inconsistent adoption, the net metering policies themselves are not uniform across states. Net metering policies vary widely across states in terms of the amount of power that can be fed back to the grid. For example, states specify penetration limits as a percentage of a distribution transformer capacity. Kerala prescribes a penetration limit of 50%, while Delhi's and Tamil Nadu's limits are 15% and 30% (BridgetoIndia, 2014). IR would need to assess the net metering potential by state and by building.

Also, to quickly achieve decarbonization targets, as a first step (Stage 1), IR could focus on states in which net metering is well implemented and where it has already identified solar rooftop potential – i.e., Tamil Nadu, Delhi, West Bengal, and Andhra Pradesh (Table 5). In the second phase (Stage 2), IR could explore the feasibility in states with notified net metering policy and in which it holds large rooftop spaces, such as Uttar Pradesh, Maharashtra, Punjab, Madhya Pradesh, and Telangana. In the later stages IR could identify rooftop space in states in which net metering is operational, such as Karnataka and Uttarakhand; as well as seek faster operationalization of net metering policy in states with identified rooftop space such as Gujarat.

OPEN ACCESS

Open access (OA) allows 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. The primary motivation for the introduction of this feature in the Indian power sector is to increase competition in the electricity supply market and reduce the power procurement cost.[19]

If IR chooses a decarbonization pathway of purchasing renewable power from independent power producers rather than captive generation, then IR will need to go through the OA route to procure power.

However, the state-level regulations around open access are not well implemented across all states. Some state DISCOMs discourage open access by levying high charges[20] or outright rejecting any inter-state trade, as they are reluctant to lose their most profitable consumers, who are usually the bulk consumers in industrial and commercial sectors.[21] Poor implementation of policies regulating open access in some states will be a challenge for IR's decarbonization plans in those states.

If IR chooses a decarbonization pathway based on purchased power, we recommend IR start by procuring clean power in the 15 states which have successfully implemented open access, shown in Table 6.

19 Open access fundamentally tries to separate the business of wires from electricity, meaning the company that owns the transmission and distribution lines in an area need not be also the supplier of electricity. Essentially, the consumers will have the freedom to choose their electricity supplier. Open access also encourages captive power generation by allowing buyers to procure power from their power plants that are located at faraway places from the demand centers.

20 Charges levied include transmission charges, distribution charges, cross subsidy surcharges, and state load dispatch center charges. Buyers also have to bear the transmission losses in electricity.

21 Typically in India electricity is subsidized for households and agriculture and these subsidies are recouped from industrial and commercial consumers in the form of cross subsidy surcharges.

5.2 Load balancing

Generating electricity from solar and wind power is essential to the decarbonization of IR. However, solar and wind power are intermittent (for example, solar power is not available at night) and variable (for example, cloud cover could cause a sudden change in solar power generation during the day). Hence, any decarbonization pathway that entails high shares of solar and wind power will require interventions to ensure consistent generation of power, called load balancing. Load balancing is achieved through a flexible power system, which can adapt to the changes in electricity generation and consumption by using technologies such as flexible generation and energy storage. However, not all of the technologies that could be used for designing a flexible power system are currently technically or economically feasible, either because the regulations surrounding the technology are not in place or the technology is still in a nascent stage.

Table 6: State of third party procurement (open access)

SL NO.	STATES	STATUS
1	Andhra Pradesh	Successfully implemented
2	Arunachal Pradesh	Successfully implemented
3	Assam	Successfully implemented
4	Goa	Successfully implemented
5	Gujarat	Successfully implemented
6	Haryana	Successfully implemented
7	Karnataka	Successfully implemented
8	Kerala	Successfully implemented
9	Meghalaya	Successfully implemented
10	Punjab	Successfully implemented
11	Rajasthan	Successfully implemented
12	Tamil Nadu	Successfully implemented
13	Telangana	Successfully implemented
14	Uttarakhand	Successfully implemented
15	Delhi	Successfully implemented
16	Chhattisgarh	Poorly implemented
17	Himachal Pradesh	Poorly implemented
18	Jammu and Kashmir	Poorly implemented
19	Madhya Pradesh	Poorly implemented
20	Maharashtra	Poorly implemented
21	Manipur	Poorly implemented
22	Mizoram	Poorly implemented
23	Nagaland	Poorly implemented
24	Odisha	Poorly implemented
25	Tripura	Poorly implemented
26	Bihar	Not allowed
27	Jharkhand	Not allowed
28	Sikkim	Not allowed
29	Uttar Pradesh	Not allowed
30	West Bengal	Not allowed
31	Union Territories	Not available

Source: State Load Dispatch Centers and power exchanges; Open Access in Indian Power Sector 2014-15 Report.

The most feasible technologies for load balancing are power banking, net metering, and pumped hydro storage.

In this context, we've examined the feasibility of various balancing technologies based on a qualitative framework, taking into consideration technical, regulatory, and commercial parameters (Figure 9). A more detailed methodology is available in Appendix 7.6.

Based on our analysis, the most feasible technology options immediately available are power banking with other DISCOMs, net metering (in some states), and pumped hydro storage. Longer term (~5 years), IR could also explore balancing through the operation of flexible thermal power plants and energy storage technologies such as batteries.

It is important to note that switching from a conventional power system to a flexible power system will involve additional costs. An accurate estimate of these balancing costs is possible only upon the complete design of the flexible power system.

Figure 9: Feasibility of Various Balancing Options

Feasibility →

Flexibility Options ↓	Low	Medium	High
Demand Response	Load shedding; Load shifting		
Flexible Supply		Flexible thermal power plants	Renewable energy forecasting
Energy Storage		Li-ion battery; Sodium-sulfur	Pumped hydro
Grid Interaction	Trading on power exchanges	Net metering with state DISCOMs	Power banking with DISCOMs

High = available for immediate deployment; Medium = would likely be feasible in 5 years; Low = would like be feasible in the long run (>5 years)

Sources: IR, CEA, GIZ, MoP, BNEF, IRENA, News reports

6. Recommendations and conclusion

The complete decarbonization of Indian Railways (IR) will not only bring India closer to its 2030 carbon emissions reduction and renewable energy targets, but will also bring savings in energy costs to IR. Further, it could provide a strategic example for other industries in the transportation sector to follow, as well as to the Indian economy as a whole.

6.1 Recommendations

For the most cost-effective and feasible decarbonization of IR, we recommend the following steps:

- Transitioning as much as possible from a diesel-powered rail network to an electrified rail network is a prerequisite for decarbonization, because there is more availability of clean electricity options than clean fuel options. Of the clean electricity options, solar and wind power are the most feasible and also provide complimentary generation profiles, which will lower the balancing costs.
- For the traction segment of IR, decarbonization through captive generation at an accelerated rate will be the most cost-effective pathway, with a savings of 32% in average annual cash outflows compared with the business-as-usual pathway.
- For the non-traction segment of IR, decarbonizing through captive generation at an accelerated rate will be the most cost-effective pathway, with a savings of 61% in average annual cash outflows compared with the business-as-usual pathway.
- In order to increase feasibility of implementation, as a first step, IR should install rooftop solar capacity in the states which have successfully implemented net metering, and in which IR owns a large amount of rooftop space. Next, IR should seek better implementation of net metering policies in those states in which it has high rooftop solar potential.
- If IR chooses a decarbonization pathway with purchased power instead of captive generation, IR should focus on purchasing renewable power from independent power producers in states where purchasing power through open access is encouraged.
- IR should utilize the most low-cost technologies for load balancing options, which are currently power banking, net metering, and pumped hydro storage currently, and tap into additional balancing options, such as flexible thermal power plants and battery storage as they become available in the future.

6.2 Future work

This study is a high-level scoping exercise to assess the decarbonization options available to IR and estimate the direct costs associated with the options identified.

The next phase of this study will be a thorough technical assessment of IR's chosen decarbonization pathway to estimate the total costs of decarbonization. This may include:

- A deeper system design of a chosen traction segment (e.g., Delhi-Mumbai Freight Corridor) or a particular state (e.g., MP), which includes load forecasting, load matching (with RE), generation system sizing, storage system design, and other balancing requirements.
- A thorough assessment of grid integration challenges associated with a complete decarbonization scenario. Challenges include transmission and distribution constraints, handling variability and intermittency of renewables etc.

7. Appendix

7.1 Methodology for electricity demand forecast

We used a compound annual growth rate (CAGR) approach to forecast the IR electricity demand till 2030. Steps used for calculations are:[22]:

(a) We collected historical electricity consumption (traction and non-traction separately) by IR from year 2008 to 2014.

(b) We collected the data of total route kms and total electrified tracks route kms.

(c) We also got the planned electrification rate per year and the expansion of total route kms from 2016 to 2019.

(d) We calculated the ratio of traction electricity consumption to the corresponding electrified tracks for previous years from 2008 to 2014. The ratio maps the electricity consumption to the total electrified tracks. The ratio was stable for all these years at 0.07%. Then, we calculated the average of these historical ratios and assumed that it will remain constant in the future as well.

(e) Then we calculated the future traction electricity demand from 2016 to 2019 using the numbers calculated in step c & d (multiplying c and d).

(f) We calculated the CAGR of traction electricity consumption from 2008 to 2019. The CAGR comprises of the historical electricity consumption growth rate and the future (till 2019) planned growth rate in the traction electricity consumption. We used this rate to forecast the traction based electricity demand until 2030.

(g) We also forecasted the non-traction electricity consumption using the assumption that 15% of the total electricity consumption is for non-traction use.

7.2 Methodology for business-as-usual cost forecast

We considered the following as business-as-usual pathways for the traction and non-traction segments:

Traction: Average power procurement cost of DISCOMs in India

Non-traction: Commercial tariffs applicable for the non-traction business segment of IR

Forecast of business-as-usual costs: We used the following techniques to forecast the business-as-usual (average power purchase cost to DISCOMs in case of traction and commercial tariff for non-traction) until 2030:

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.

7.3 Forecast of renewable energy technology costs:

We forecasted the unsubsidized levelized cost of renewable electricity until 2030. The forecast of levelized costs are driven by the forecasts of certain variables that act as inputs for a project-level cash flow model used to estimate the levelized cost of electricity for plants commissioned each year from 2016 to 2030. Several factors, such as return on equity, interest rates, capital expenditure, and capacity utilization factor influence the levelized cost of electricity.

Using project-level cash flow models and sensitivity analysis, we assessed the responsiveness of levelized cost of renewable energy to these factors. The levelized costs of renewable energy are highly sensitive to capital expenditure and capacity utilization. Hence, these two variables form the key inputs into the cash flow model used to calculate the levelized cost of electricity for solar and wind energy. We took capacity utilization factor forecast from IESS tool[23] (developed by NITI Aayog). The assumption table used to calculate the unsubsidized LCOE is mentioned as below:

The methodology used to forecast the capital expenditure until 2030 is mentioned as below:

22 Historical data was collected from IR's Yearbooks and Achievement Booklets

23 http://indiaenergy.gov.in/

We used regression analysis as our main approach to forecast the capital expenditure of grid connected solar PV and onshore wind power projects in India. We used multi-factor ordinary least squares (OLS) regression technique represented by the following equation:

$$Y = \beta o + \Sigma_{i=1}^{n} \beta_i X_i$$

where the dependent variable Y is the capital cost of the renewable power plant and Xi are the independent variables. We used a natural log transformation of all the variables so that the error sample is closer to the normal distribution.

As usual practice, we divided total capital cost of renewable power projects into two components: turbine cost (for onshore wind)/module cost (for solar PV) and Balance of Systems (BOS) cost. Given different drivers (Nemet, 2006; Pillai and Cruz, 2013; Berry, 2009; Neij, 1997), we tried to estimate module/turbine cost and BOS cost separately. Based on Huneteller et al. (2014), we also distinguished between global and local learning effects.

The Module/Turbine-Related factors are as follows:

- Learning-by-doing: Learning-by-doing refers to process improvements due to cumulative experience with producing a particular technology. This is typically represented by cumulative global deployment (CGD) of the technology.
- Scale: Scale refers to economies of scale in production. We used annual global deployment (AGD), or market demand, as a proxy to measure scale. Since annual deployment measures scale at the industry level, it indicates market maturity as well as inbuilt efficiencies.
- Technology/R&D: Technology refers to improvements in solar modules (e.g., efficiency) or wind turbines (e.g., rotor diameter). Module efficiency can be captured as power output per square meter (Watt/m2).
- Input costs: This refers to the cost of raw material used to create solar modules or wind turbines. In the case of solar, silicon is the primary input. For wind, steel and electrical machinery are significant components. We used the world consumer price index (CPI) to capture the effect of input cost.

Similarly for the BOS component of the capital cost, we identified following factors:

- Learning-by-doing: In this case, learning is captured by cumulative local deployment (CLD) which refers to the total solar/wind capacity deployed in India. Similar to global learning, this is used as an indicator of local level learning effects.
- Scale: Similar to global annual deployment, annual local deployment (ALD) indicates the increase in the scale of the solar/ wind market within India (at country level).
- Input cost: Inflation in the cost of system components (inverter, land cost, labor cost, etc.) would drive overall BOS cost. These variables can be captured using relevant inflation indices. We used India's wholesale price index (WPI) as a proxy for the input cost.

We next discuss the regression analysis separately for solar and wind.

SOLAR CAPITAL COST FORECAST:

Solar capital expenditure consists of module and BOS costs (Malla & Niraula, 2012). We use two separate regression equations: one for each. We used a one factor experience curve (OFEC) as well as a multifactor experience curve (MFEC) for forecasting the module and BOS cost.

Solar PV module cost forecast: The market for PV modules is global; hence we used global level independent variables over 35 years (1980-2015). The (yearly) regression equation is below:

$$ln(Module\ Cost\ (PV)) = \beta_o + \beta_1 ln(CGD_s) + \beta_2 ln(AGD_s) + \beta_3 ln(Inf_g) + \beta_4 ln(ME)$$

where Module Cost (PV) is the average module cost; CGDs is the cumulative global deployment capacity of solar; AGDs is the annual global deployment capacity of solar; Infg is the global inflation (consumer price index); and ME is the module efficiency of solar PV.

Solar BOS (non-module) cost forecast: BOS cost are driven by local factors. Based on data availability in India, we used historical data of 7 years (2009-2015). The (yearly) regression equation is mentioned as below:

$$ln(BOS) = \beta_o + \beta_1 ln(CLD_s) + \beta_2 ln(ALD_s) + \beta_3 ln(Inf_l)$$

where BOS is the average BOS cost of solar plant, CLDs is the cumulative local (India) deployment capacity of solar; ALDs is the annual local (India) deployment capacity of solar; Infl is the local (India) inflation (consumer price index).

ASSUMPTIONS	SOLAR	WIND
POWER GENERATION		
Capacity Utilization Factor (P50 PLF)	Based on IESS forecast	Based on IESS forecast
Useful Life	25 Years	25 Years
CAPITAL COST		
Capital Cost (INR million/MW)	Based on forecast of solar plant capital cost	Based on forecast of wind plant capital cost
OPERATING EXPENSE		
O & M Expenses(1st Year)	INR 0.7 million/MW	INR 1.12 million/MW
Fuel Cost Expenses (1st Year) including transportation cost	NA	NA
Escalation in O & M Expenses	Based on Inflation forecast	Based on Inflation forecast
Escalation in Fuel Cost and Transportation Cost	NA	NA
FINANCIAL ASSUMPTIONS		
Debt to Equity Ratio	70:30	70:30
Minimum Debt Service Coverage Ratio (DSCR)[2]	1.3	1.3
DEBT		
Repayment Period	12 years	12 years
Interest Rate (Fixed)	12.76% (for IPP) 8.28% (for IR)	12.76% (for IPP) 8.28% (for IR)
EQUITY		
Expected Return on Equity (Post tax)	16% (for IPP) 14% (for IR)	16% (for IPP) 14% (for IR)
Cost of Capital for IR = 8.03% Cost of Capital for IPPs = 10.70%		
TAX INCENTIVE		
Tax Holiday	10 years	10 years
Minimum Alternative Tax	20%	20%

WIND CAPITAL COST FORECAST:

Wind capital cost has two broad components: Turbine and BOS. Turbine costs constitute about 65-84% of the total system cost (IRENA, 2012). Though it would have ideal to run separate regressions, due to the non-availability of the cost split, we ran the regression with total system cost only. We used historical data of 16 years (from 2000 to 2015). The (yearly) regression equation is mentioned as blow:

$$1.\ ln(Total\ Capital\ Cost) = \beta_o + \beta_1 ln(CGD_w) + \beta_2 ln(AGD_w) + \beta_3 ln(CLD_w) + \beta_4 ln(ALD_w) + \beta_5 ln(Inf_I)$$

where total capital cost is the average system cost;[24] CGDw is the cumulative global deployment capacity of wind[25]; AGDw is the annual global deployment capacity of wind; CLDw is the cumulative local (India) deployment capacity of wind[26]; ALDw is the annual local (India) deployment capacity of wind; Infl is the local (India) inflation (consumer price index).

24 Data Source: BNEF Database

25 Historical Data Source: Capacity numbers are from BP Statistical review 2015; Forecast for global capacity is based on the hi-REN scenario proposed in the technology roadmap, IEA 2013.

26 Historical Data Source: BP statistical review 2015 (Dropbox\CPI-India Database\Data); Forecast Data Source: Till 2022 we used target of 60 GW by 2022 announced by GoI and 2050 target are from India's CO2 emissions Pathway to 2050 http://www.metoffice.gov.uk/media/pdf/b/f/AVOID_WS2_D1_41.pdf (Page 20)

ISSUE OF CAUSALITY VS CORRELATION IN FORECASTING

We found that most of the independent variables were highly correlated; however, this is not too concerning for forecasting purposes (Besley, 1984). The paper suggests that when the estimation equation gets spurious (including signs of the coefficients), then one can forecast the dependent variable using the same estimation equation given the condition that the collinearity among the independent variable continues to exist in the forecast period as well. If the condition does not hold true, then multi-estimation forecasting is required which is explained in details in the paper mentioned.

In case of solar module MFEC approach, we find that the multicollinearity amongst the independent variables (all four) continue to exist in the forecasting period as well, hence we went ahead with the regression equation with all the variables for the forecasting. Although we forecasted the BOS using all the three factors (local learning effect, local scale effect and the local inflation), the resultant total system cost forecast for the solar PV module were completely out of line. Therefore, in case of BOS forecasting we used only one factor (local learning effect) equation for the final forecast.

PARAMETER	HISTORICAL DATA SOURCE	FORECAST DATA (2016-2050) SOURCE	DESCRIPTION
Module cost (PV)	Bloomberg	Not applicable	Dependent variable
Cumulative global deployment capacity of solar (CGD_s)	Data from 1980 to 2010: EPIA Data from year 2011 to 2015: BP Statistical Review-2015	IEA Technology Roadmap-2014 (Solar PV)	A global capacity forecast has been done based on 2ds scenario till 2030. We used a CAGR approach to get the yearly targets based on the milestone targets (2030, 2050 etc.) given in the report
Global Inflation (consumer price index), (Inf_g)	World Economic Outlook, IMF	CPI inflation till 2030 was done by extrapolating the linear trend equation of historical series.	
Module efficiency of solar PV (ME)	NREL and IRENA	IEA Technology Roadmap-Solar PV (2010)	Used a CAGR approach to get the yearly numbers.
BOS cost of solar plant in India (BOS)	CERC Yearly Tariff Orders from 2009 to 2015	Not applicable	Dependent variable
Cumulative local (India) deployment capacity of solar (CLD_s)	BP Statistical Review-2015	Till 2022: MNRE Beyond 2022: IEA Technology Roadmap-2014 (Solar PV)	India cumulative capacity targets are based on grid connected 60 GW target by 2022 and after that the projections are based on 2DS (Two degree by 2050 scenario) target for India proposed by IEA, 2014. We used a CAGR approach to get the yearly targets.
India Inflation (Inf_I)	Inflation.eu	Trading Economics[3]	The only source where the forecast for India CPI till 2030 is available is Trading Economics.
Total system cost of wind projects in India (Total capital cost)	BNEF Database	Not Applicable	We took the weighted average (per MW) of the total system cost of the wind power projects set up in India in each year from 2000 to 2015.
Cumulative global deployment capacity of wind (CGD_w)	BP Statistical Review-2015	IEA Technology Roadmap-Onshore Wind (2013)	Used a CAGR approach to get the yearly numbers.
Cumulative local deployment capacity of wind (CLD_w)	BP Statistical Review-2015	Till 2022: MNRE Beyond 2022: India's CO2 emissions Pathway to 2050 Metoffice.gov.uk (Page 20)	Used a CAGR approach to get the yearly numbers.

In case of wind, all the factors were significantly correlated except annual wind capacity addition in the forecasting period. Hence, in the final estimation equation we dropped this variable. Also, due to the non-availability of a forecast for the rotor diameter (efficiency factor) we had to drop this variable from the regression. Hence, we used a total of four factors (cumulative global wind deployment, cumulative local wind deployment, annual local wind capacity addition and the local inflation) in the regression.

7.4 Estimation of decarbonization costs:

Based on demand forecasts, we estimated the required renewable energy supply to meet 100% of the IR electricity demand through renewable energy supply options. To meet the required renewable energy supply, we selected solar power (ground-mounted and rooftop) and wind power as the supply options by using metrics such as construction times and regulatory delays.

We used two main scenarios to estimate the renewable energy supply based on the rate of decarbonization:

a) Accelerated rate of decarbonization: Under this scenario, we assumed that IR electricity demand will be completely met through renewable energy supply options by 2020.

b) Normal Rate of decarbonization: Under this scenario, we used the CAGR approach to achieve the decarbonization target by 2030. Currently, IR generates 0.03 TWh and 0.06 TWh of electricity from its captive solar and wind power plants respectively[27]. Based on the estimated renewable energy supply requirement and the current renewable energy generation of IR, we calculated the target CAGR to meet 100% IR electricity demand through renewable energy sources by 2030.

In the following section, we discuss the scenarios for the traction and non-traction segments' electricity supply.

Supply Scenarios:

We classified renewable energy supply scenarios into two main categories:

a) All procurement: Under this option, IR would procure all the required power from external sources.

b) All captive generation: With this option, IR would invest and set up its captive renewable energy projects first on its own land and rooftop and would acquire additional land, if required.

For each category, we designed three renewable energy supply pathways:

c) Least cost pathway: Under this pathway, we selected the least cost renewable energy option (in a particular year) in terms of landed cost of power (LCOE + Open access charges (including cross subsidy surcharge)).

d) Solar and wind mix pathway: In this pathway, we mimic the renewable energy mix (solar and wind) suggested by NITI Aayog under their high renewable energy pathway mix for India.

Hence, in total we would be creating 8 supply scenarios (2 models of procurement*2 pathways*2 decarbonization targets).

7.5 Status of net metering

Table 7.5: State of net metering policy, 2016 indicates the status of the implementation of net metering policy across the states in India.

7.6 Rating of balancing options

We considered three parameters for assessing the feasibility of balancing options, which can be further broadly classified as technical, regulatory, and commercial. We ranked each of the balancing technologies on a scale of 1-3, indicating 1 as low feasibility, 2 as medium feasibility, and 3 as high feasibility. We assigned equal weights (50:50) to non-commercial and commercial parameters. Based on the weights and individual scores, we arrived at an overall rating based on the following scale: A total score in the range of 1-1.5: Low; 1.5-2.5: Medium; 2.5-3: High. The results are presented in Table 7.6 Rating of balancing options.

27 Source: http://www.indianrailways.gov.in/brochure_inside_pages_combine.pdf

7.5 State of net metering policy, 2016

SL NO.	STATES	POLICY ANNOUNCED (Y/N)	STATE OF THE POLICY (DRAFT STAGE/ NOTIFIED)	NET METERING OPERATIONAL (ACTIVE CONNECTIONS)	RANKING
1	Andhra Pradesh	Yes	Notified	Yes	1
2	Arunachal Pradesh	No			4
3	Assam	Yes	Notified		2
4	Bihar	Yes	Notified		2
5	Chhattisgarh	Yes	Notified		2
6	Goa	Yes	Notified		2
7	Gujarat	Yes	Draft stage		3
8	Haryana	Yes	Notified		2
9	Himachal Pradesh	Yes	Notified		2
10	Jammu and Kashmir	Yes	Notified		2
11	Jharkhand	Yes	Notified		2
12	Karnataka	Yes	Notified	Yes	1
13	Kerala	Yes	Notified		2
14	Madhya Pradesh	Yes	Notified		2
15	Maharashtra	Yes	Notified		2
16	Manipur	No			4
17	Meghalaya	No			4
18	Mizoram	No			4
19	Nagaland	No			4
20	Odisha	Yes	Notified		2
21	Punjab	Yes	Notified		2
22	Rajasthan	Yes	Notified		2
23	Sikkim	Yes	Notified		2
24	Tamil Nadu	Yes	Notified	Yes	1
25	Telangana	Yes	Notified		2
26	Tripura	No			4
27	Uttar Pradesh	Yes	Notified		2
28	Uttarakhand	Yes	Notified	Yes	1
29	West Bengal	Yes	Notified	Yes	1
30	Delhi	Yes	Notified	Yes	1
31	Union Territories	Yes	Notified		2
	Total	**Yes: 25; No: 6**	**Notified: 24; Draft stage: 1**	**6**	

Sources: Bridge to India, Intersolar, MNRE, Bijili Bachao, CleanTechnica, Respective state electricity regulatory commissions

Ranking Methodology: Operational net metering policy -1; Notified net metering policy – 2; Net metering policy in draft stage: 3; No net metering policy - 4

7.6 Rating of balancing options

TYPE	TECHNOLOGY	NON-COMMERCIAL		COMMERCIAL	OVERALL RATING
		TECHNICAL COMPATIBILITY	REGULATORY FEASIBILITY	COMMERCIAL FEASIBILITY	
Demand Response	**Load shedding**	Not compatible with IR's business model. Rating: Low	Some regulatory pressure could be expected on IR to run trains efficiently. Rating: Medium	Load shedding will impact revenues of IR. Rating: Low	**LOW**
	Load shifting	IR's traction demand is not flexible. Rating: Low	No regulatory changes required. Rating: High	Load shifting is not possible for IR due to under-capacity of tracks. Rating: Low	**LOW**
Flexible Electricity Supply	**Flexible thermal power plants**	Turndown capability of Indian thermal power plants is lower than international average. Other challenges include poor quality of generation/ load forecasting. Rating: Medium	Regulations and standards need to be established for balancing capacity. Rating: Low	There is no clear understanding of costs in the absence of compensation framework for thermal power plants used for balancing purposes. Rating: Medium	**MEDIUM**
Energy Storage	**Pumped Hydro**	Most flexible and fast reacting balancing option. A total of 2,600 MW of pumped hydro storage is operational. Rating: High	Regulations are required to design incentive mechanism for hydro power plants to be used for renewable energy balancing. Rating: Medium	Among the conventional power plants, pumped hydro would be the cheapest for balancing. Rating: High	**High**
	Batteries (Li-ion)	Lithium-ion technology is the most matured and has early lead among battery technologies. Rating: High	No regulatory changes required. Rating: High	Costs vary by application. In general, levelized cost of Li-ion batteries is expected to reduce by 50% from ~INR 14.08/kWh in 2015 to ~INR 3.84/kWh by 2025. Rating: Medium	**Medium**
	Sodium-sulfur (NaS)	Mature technology with an installed capacity of over 450 MW globally. Rating: High	No regulatory changes required. Rating: High	Current cost at utility scale is ~INR 16.64/kWh, which is estimated to reduce to ~INR 4.48/kWh by 2025. Rating: Medium	**Medium**
Balancing with Grid	**Trading on power exchanges**	Buying and selling on exchanges is currently only possible on day-ahead basis. Also, no renewable energy power is traded due to lack of forecasting and scheduling. Rating: Low	For balancing requirements, real-time markets such as two hours-ahead markets have to be developed, for which regulatory framework is required. Rating: Low	Currently, prices of power traded on the exchanges are in the range of INR1.5-3.0/kWh. Hence, selling on the exchange would be at a loss if the current market conditions continue, while buying could be profitable. Rating: Medium	**Low**
	Banking with State discoms	IR currently has a banking arrangement with MP. This could be replicated with other states and would be ideal for load balancing of IR. Rating: High	No regulatory changes required. Rating: High	Currently, IR has a banking arrangement with MP for 50 MW at INR 0.10/kWh, which is almost at a negligible cost. This arrangement could be replicated with other DISCOMs. Rating: High	**High**
	Net metering with state discoms	Applicable for rooftop systems. Already operational in India. Rating: High	Regulatory intervention is needed for better implementation. Rating: Low	IR will be using net metering for non-traction segment and at commercial tariffs net metering will be commercially viable. Rating: High	**Medium**

8. References

BioEnergy Consult, 2015; Biomass Sector in India – Problems and Challenges; http://www.bioenergyconsult.com/biomass-india/

Biopower, Jan-Mar 2014; Study on Performance/Viability of Biomass-based Power Plants; http://mnre.gov.in/file-manager/biopower/BioPower-Jan-Mar-14.pdf

BridgetoIndia, 2014; Kerala Announces a Draft Net Metering Policy; http://www.bridgetoindia.com/blog/weekly-update-kerala-announces-a-draft-net-metering-policy/

Business Standard, 2015a; 18 Interesting Facts about India Railways; http://www.business-standard.com/article/beyond-business/18-interesting-facts-about-india-railways-business-standard-news-115021600404_1.html

Business Standard, 2015b; Indian Railways Signs First Bilateral PPA to Cut Energy Costs; http://www.business-standard.com/article/economy-policy/indian-railways-inks-first-bilateral-ppa-to-cut-energy-costs-115020700481_1.html

CERC, 2015a; Order in Petition No. 197/MP/2015; http://www.cercind.gov.in/2015/orders/SO197N.pdf

CERC, 2015b; Roadmap for States to Achieve Reliable Grid Management and Large Scale Integration of Variable Renewable Energy Sources; http://cercind.gov.in/2015/whatsnew/ATG.pdf

CleanTechnica, 2016; India May Target 10 GW of Geothermal Capacity by 2030; http://cleantechnica.com/2016/06/16/india-may-target-10-gw-geothermal-capacity-2030/

CPI, 2016; The Potential of Institutional Investors to Help Meet India's Renewable Energy Targets (Working Paper)

EAI, 2014; India Geo-thermal Energy; http://www.eai.in/ref/ae/geo/geo.html

Economic Times, 2016; Government Mulls Electrification of 35,000 KM Rail Line in 3 Years; http://economictimes.indiatimes.com/industry/transportation/railways/government-mulls-electrification-of-35000-km-rail-line-in-3-years/articleshow/51244115.cms

FoR, 2015; Model Regulations on Forecasting, Scheduling and Deviation Settlement of Wind and Solar Generating Stations at the State level; http://www.forumofregulators.gov.in/Data/study/MR.pdf

ICRIER, 2016; De-carbonization of Indian Railways: Project Plan (Phase 1) – Working Paper

IR Budget, 2014-15; http://www.indianrailways.gov.in/railwayboard/uploads/directorate/finance_budget/2014-15_Final/Budget%20Speech%202014-15%20Highlights%20_English_PDF.pdf

NCE, 2014; Better Growth, Better Climate; http://newclimateeconomy.report/2014/

NTDPC, 2013; National Transport Development Policy Committee Report on Railways; http://planningcommission.nic.in/sectors/NTDPC/volume3_p1/railways_v3_p1.pdf

Open-Access, 2016; Analysis of Draft Regulations on Forecasting and Scheduling of wind and Solar Generating Stations; http://reconnectenergy.com/blog/2016/03/analysis-of-draft-regulations-on-forecasting-and-scheduling-of-wind-and-solar-generating-stations-rajasthan/

PWC, 2014; Hydropower in India: Key enablers for a better tomorrow; https://www.pwc.in/assets/pdfs/publications/2014/hydropower-in-india-key-enablers-for-better-tomorrow.pdf

PIB, 2016; Minister of Railways inaugurates International Conference on Decarbonization of Indian Railways - Mission Electrification; http://pib.nic.in/newsite/PrintRelease.aspx?relid=153230

The Wire, 2015; Where Will Nuclear Power Plants of the Future Be Built?; http://thewire.in/2228/where-will-nuclear-power-plants-of-the-future-be-built/

UNDP, 2015; Improving Energy Efficiency in the Indian Railways System; http://www.in.undp.org/content/india/en/home/operations/projects/environment_and_energy/improving_energyefficiencyintheindianrailwaysystem.html