Indian Railways Opportunity for Connecting Solar PV Generation

Assessment of potential for direct traction energy supply with private wire solar PV connection
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Riding Sunbeams is a world-leading innovator on a mission to power the world’s railways with direct supply from solar PV, while maximising social benefits for line-side communities.

www.ridingsunbeams.org

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## Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>CEA</td>
<td>Central Electricity Authority</td>
</tr>
<tr>
<td>CO2</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>GW / GWh</td>
<td>Gigawatt / Gigawatt hour</td>
</tr>
<tr>
<td>JV</td>
<td>Joint Venture</td>
</tr>
<tr>
<td>kW / kWh</td>
<td>Kilowatt / Kilowatt hour</td>
</tr>
<tr>
<td>MW / MWh</td>
<td>Megawatt / Megawatt hour</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>tCO2e</td>
<td>Tonne of Carbon Dioxide Equivalent</td>
</tr>
<tr>
<td>TW / TWh</td>
<td>Terawatt / Terawatt hour</td>
</tr>
<tr>
<td>DISCOM</td>
<td>Power Distribution Companies</td>
</tr>
</tbody>
</table>
Introduction

In July 2020, the Indian Government announced that Indian Railways will move to 100 per cent electrification in the next three-and-half years (by end of 2024)\(^1\). The target of 100 % electrification had initially been announced for completion by 2022.\(^2\) As of March 2020, Indian Railways recorded 39,329 km of electrified route kilometres. This represents 58% of Indian Railways total route kilometres\(^3\). Indian Railways has a target of electrifying an unprecedented 7,000 route kilometres in 2020–21.Once the programme is complete, Indian Railways will be the largest electrified rail network in the world.

Around two-thirds of the freight and more than half of the passenger traffic is already transported by electric traction, but accounts for just 37% of Indian Railways’ total traction energy costs. The Indian Government expect that electrifying their network will reduce the energy costs by 1,351 million rupee (£13.45 million) per day.

Many of the electrified lines connect the large population centres of Mumbai, Delhi and Kolkata. India uses the 25 kV AC electrification system. All previous DC traction was removed except for the 1.5 kV DC network in Mumbai\(^4\). The railway network map is shown in Figure 1.

Indian Railways is split into 18 railways zones of which 16 are considered for this study\(^5\). The two zones not considered are the Metro zone and the new South Coast railway management zone\(^6\). The headquarters of each management zone considered in this study are in Table 1.

In 2017, Indian Railways launched an ambition to reduce their carbon emissions to 33 % of the 2005 levels by 2030. This is to be achieved through both energy efficiency measures (8-13% reduction from 2013 levels) and increasing the amount of traction energy from renewable generation. At the beginning of 2020, this target was accelerated and India’s railway minister, Piyush Goyal announced that the fleet of trains would be a net-zero carbon emitter by 2030.

Direct connection of solar PV is one key method to allow Indian Railways to meet this target. Indian Railways plan to install 20 GW of solar for both traction and non-traction loads as part of their effort to reach net-zero by 2030. About 51,000 hectares of land has been identified as suitable for new solar developments to meet this target. Indian Railways and the Ministry of Railways have formed a joint venture (JV), the Railway Energy Management Company to support the development of new renewable energy projects to meet the railway’s growing energy demand\(^7\). Indian Railways intends to source energy from 1 GW of new solar PV installed on their property portfolio by the end of 2021. Half of the solar PV, 0.5 GW, will be installed on railway building roof-tops to supply non traction demand, for example station loads and level crossing loads. The other half (0.5 GW) will be procured from ground-based solar arrays on

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1. https://www.hindustantimes.com/india-news/100-electrification-in-railways-in-next-3-5-years-piyush-goyal/story-rf1Kg8324nJ06G86w1twXL.html
2. https://www.livemint.com/Companies/jD73mHWeUf3hPv0WvHf1/Covt-approves-100-electrification-of-railways-by-202222.html
5. https://indianrailways.gov.in/railwayboard/view_section.jsp?lang=0&sid=0,1,304,366,533,1007,1012
vacant railway land to supply the traction loads, primarily through slewing Power Purchase Agreements via DISCOMs.

However, Indian Railways, in collaboration with Bharat Heavy Electricals Limited have developed a pilot site with 1.7 MW of solar PV generation at Bina, Madhya Pradesh that is providing energy to run trains through direct connection to the railway traction network. The demonstrator scheme is intended to prove the viability of direct traction supply so that the 3GW of solar PV Indian Railways tendered for in 2020 can be connected directly to their traction network without needing to connect via India’s electricity grid. This is the same approach Riding Sunbeams has been pursuing in the UK.

India has large amounts of solar resource available due to its latitude between 8° 4’ north to 37° 6’ north. The higher generation and utilisation rates should greatly improve the economics of direct solar traction supply. This report aims to estimate the total share of Indian Railways traction load which could be met with direct supply from solar.

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Table 1: List of the Railway Zones and their headquarters.

<table>
<thead>
<tr>
<th>No</th>
<th>Name of the Railway Zone</th>
<th>Zonal Headquarter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Central Railway</td>
<td>Mumbai</td>
</tr>
<tr>
<td>2</td>
<td>Eastern Railway</td>
<td>Kolkata</td>
</tr>
<tr>
<td>3</td>
<td>East Central Railway</td>
<td>Hajipur</td>
</tr>
<tr>
<td>4</td>
<td>East Coast Railway</td>
<td>Bhubaneshwar</td>
</tr>
<tr>
<td>5</td>
<td>Northern Railway</td>
<td>Baroda House, New Delhi</td>
</tr>
<tr>
<td>6</td>
<td>North Central Railway</td>
<td>Allahabad</td>
</tr>
<tr>
<td>7</td>
<td>North Eastern Railway</td>
<td>Gorakhpur</td>
</tr>
<tr>
<td>8</td>
<td>North Frontier Railway</td>
<td>Maligaon, Guwahati</td>
</tr>
<tr>
<td>9</td>
<td>North Western Railway</td>
<td>Jaipur</td>
</tr>
<tr>
<td>10</td>
<td>Southern Railway</td>
<td>Chennai</td>
</tr>
<tr>
<td>11</td>
<td>South Central Railway</td>
<td>Secunderabad</td>
</tr>
<tr>
<td>12</td>
<td>South Eastern Railway</td>
<td>Garden Reach, Kolkata</td>
</tr>
<tr>
<td>13</td>
<td>South East Central Railway</td>
<td>Bilaspur</td>
</tr>
<tr>
<td>14</td>
<td>South Western Railway</td>
<td>Hubli</td>
</tr>
<tr>
<td>15</td>
<td>Western Railway</td>
<td>Churchgate</td>
</tr>
<tr>
<td>16</td>
<td>West Central Railway</td>
<td>Jabalpur</td>
</tr>
</tbody>
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Modelling Approach

The profile of solar PV generation in each region of India is required to be compared with the regional traction demand profile to calculate the total amount of direct wire PV generation that could be supplied to Indian Railways.

India has a good solar PV resource of between 1,400 kWh/m² and 1,800 kWh/m² per year. The profile of solar PV generation for India is available from the EU Science Hub’s photovoltaic geographical information system. Annual output and hourly data between 2005 and 2016 is available and assumes a PV system loss of 14%.

The headquarters for each of the railway zones was selected for the solar PV output during the year 2015, except Western Railway where Vadodara was selected instead of Churchgate which is an area in Mumbai and is also the headquarters of Central Railway. Selecting Vadodara, inside the Western Railway region, provided a better distribution of solar PV samples across India.

The selected location for the solar PV generation of each location is shown in Figure 1 and the annual output shown for 1 MW of solar PV generation installed is shown in Figure 2.

Figure 1: Map showing the location selected for the region solar PV location for each of the 16 railway management zones.

The average hourly profile, Figure 4, averaged from the 16 sites selected has an annual output of 1,564 MWh for each MW of capacity installed. There is a reduction in solar PV output during the summer months, this is likely due to the monsoon season causing increased cloud cover and reducing the solar output.

Indian Railways’ use electricity, diesel, and coal to provide the traction energy. The annual energy consumption is available from the Indian Railways annual year report. Statistics for 2018-2019 have been used to avoid any reduction in annual energy consumption due to the COVID pandemic in 2020. In 2018-19, Indian Railways used 17.682 TWh of electricity, 2.749 billion litres of diesel and one thousand tonnes of coal. Coal is very small percentage of the annual energy usage and has been omitted for this study.

The diesel consumption was converted to an equivalent kWh electricity usage to model the Indian Railways network assuming full electrification. A conversion of 10 kWh per litre of diesel and a diesel engine efficiency of 43% was assumed. The reported usage of 2,749 billion litres of diesel, using the stated assumptions is an equivalent of 11,820.7 GWh of electricity. The conversion from diesel to electric does not consider efficiency savings when the train is idle during part load operation or energy captured from regenerative braking. A diesel train will consume diesel when the engine is idle, unlike for an electric train where the motor only consumes energy when the train is moving. The efficiency of the diesel engine will reduce during part load operation. Modern power electric drives on electric trains can maintain higher efficiencies for the motor across the operational range of the train. Energy increases have also not been considered from installing air conditioning in new carriages or electric trains operating at higher speeds than their diesel counterparts.
The Indian Railways Annual Year Book reports the energy usage for each of the 16 railway zones. However, the total energy usage reported here is not the same as reported in the Indian Railways Statistical Summary. The energy usage for each of the 16 railway zones has been adjusted such that the total annual energy usage matches as reported in the Statistical Summary.

Two alternative daily traction profiles were assumed for the model, a flat profile and a commuter profile. The flat profile assumed the traction demand was constant every day of the year between the hours of 04:00 and 23:00. The traction energy demand was divided by 7,300 hours of operation per year (20 hours a day for 365 days per year). An hourly energy consumption was calculated to be 2,422 MWh for the electric traction and 1,619 MWh for the diesel traction (4,041 MWh for the combined electric and diesel traction).

The commuter profile assumed a morning and evening peak which has been observed on traction networks in the UK. The morning peak was for two hourly periods at 07:00 and 08:00 at 3,800 MWh for the electric traction and 2,540 MWh for the diesel traction (6,340 MWh for the combined electric and diesel traction). The evening peak was for two periods between 18:00 and 19:00 at 3,420 MWh for the electric traction and 2,286 MWh for the diesel traction (5,706 MWh for the combined electric and diesel traction). The midday demand which is when the solar output is at daily maximum was less than the hourly flat profile demand at 1,520 MWh for the electric traction and 1,016 MWh for the diesel traction (2,536 MWh for the combined electric and diesel traction). This represents a reduction of 60% from the midday demand when assuming a flat profile. The two modelled profiles are shown in Figure 4.
A presentation by Indian Railways discussing the use of solar PV power for allowing Indian Railways to meet decarbonation targets assumes the railway demand profile is flat\(^\text{14}\); providing some confidence that using a flat profile is a suitable approach. Rail traffic in India does not appear to be so dominated by daily commuter flows in and out of large cities as in the UK.

The assumed hourly demand of each railway zone is compared with the hourly solar PV output associated with that railway zone. For direct wire solar PV generation connected to the traction network without any export limitation scheme or storage technology, the solar PV generation will either be used by the trains in the electrical section or exported at the railway’s nearest grid supply point back into the transmission network.

Comparing the energy demand of the traction system with the estimated solar PV generation for each hour by hour for a one-year period allows the model to calculate the utilisation of the solar PV generation. The utilisation is defined as the ratio between the amount of solar PV generation that can be used to supply the traction demand and the total solar PV generation.

For each hour period, if the solar PV generation is less than or equal to the traction demand, it is assumed all the solar PV generation can be used by the traction demand. The remainder of solar generation greater than the traction demand is either exported at the grid supply point, curtailed, or could be used to charge line-side storage for use when the output of the solar PV generation reduces. The magnitude of PV generation for each railway zone is scaled to ensure there is not more than 1 GWh of solar PV generation which is not available to be used to supply the traction demand.

\(^{14}\) https://www.railsaver.gov.in/documents/RUMSL.pdf

Figure 4: Modelled daily profiles for the Indian Railway network, the top shows a flat profile and the bottom shows a typically profile where commuting is driving the demand for train services.
The outline of the algorithm used to calculate the amount of traction demand that could be supplied by direct wire solar PV generation is in Figure 5.

The Central Electricity Authority (CEA), a division of the Ministry of Power in the Government of India publishes the generation and CO2 emission data for India\(^\text{15}\). In 2018–19 India’s net generation total was 1,165 TWh and as reported by the CEA, the absolute emissions total was 960,898,915 tCO2e. The CO2 emissions from electricity in India, calculated from the generation total and emissions total, is 825 tCO2e / GWh. In comparison the UK’s CO2 emissions from electricity consumed in residential and business premises is 256 tCO2e / GWh\(^\text{16}\). The Indian emissions are over three times higher per unit of electricity than the emissions from the UK because of the much higher percentage of coal generation on the Indian electricity system. CO2 emissions from coal generation are approximately 870 tCO2e/CWh of electricity supplied, and coal continues to dominate India’s electricity supply mix.

Solar PV has zero CO2 emissions per energy generated (excluding emissions from manufacturing and installation) and therefore for every 1 GWh of electricity that is supplied to Indian Railways, the CO2 emissions are reduced by 825 tCO2e. Incidentally the CO2 emissions from diesel are 2.687 tCO2e\(^\text{17}\) per 1,000 litres which is less than the equivalent CO2 emissions of 3.546 tCO2e per 1,000 litres from India’s generation mix. The reported annual diesel usage in 2018/19 was 2,749 billion litres\(^\text{18}\). At 2.687 tCO2e per 1000 litres this has a CO2 emission of 7,386,571 tCO2e. Converting the diesel usage to electricity using a conversion rate of 10 kWh / litre and a diesel engine efficiency of 43% equals 11,820.7 GWh of electricity. This would require a 1% increase in India’s electricity generation of which in 2018–19 was 1,165,160 GWh. CO2 emissions for electricity are 825 tCO2e/CWh which for 11,821 GWh of electricity equals 9,748,453 tCO2e. Converting all the diesel traction to electricity will cause a 32% increase in CO2 emissions because of India’s current reliance on coal to produce electricity. These numbers

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15. https://cea.nic.in/cdm-co2-baseline-database/?lang=en


17. Referenced from UK greenhouse gas reporting conversion factors 2019 for mineral diesel

presented have been rounded and assumes the existing grid is able to provide the increased demand of approximately 11,821 GWh from a 100%.

## Results from the Model

For a fully electrified Indian Railways traction network, and using the modelling approach presented in the previous section, the amount of solar PV generation that can be connected to the Indian Railways network by totalling the outputs from the 16 railway zones is estimated to be 5,272 MW for the flat profile and 3,338 MW for the commuter profile. The energy output from connecting the solar PV generation is expected to be 8,296 GWh for the flat profile and 5,251 GWh for the commuter profile. For both the flat and commuter profiles, the connected PV generation achieves utilisation of 99.9% which can be used by the traction demand. The 0.1% of generation that cannot be used and will likely be exported at the grid supply point is a maximum of 1 GWh per year.

Connecting 5,272 MW for the flat profile and 3,338 MW for the commuter profile is expected to supply 28% of the traction demand for the flat profile and 18% of the traction demand for the commuter profile. Connecting the PV generation would reduce CO2 emissions by 6,840,875 tCO2e per annum for the flat profile and 4,329,906 tCO2e for the commuter profile. This is based on 100% electrification of the Indian Railway where the electricity supplied from the grid has CO2 emissions of 825 tCO2e/GWh as published by the CEA.

The commuter profile has a reduced capacity for the connection of PV generation because the expected load during the peak of solar generation at solar noon is 60% lower than the flat profile. Connecting more PV generation would allow for more solar PV generation to be connected, however not all of the energy generated by the solar PV
generation could be directly used by the traction network. This excess generation would either need to be exported at the grid supply point, curtailed or used to charge batteries.

The estimated theoretical total generation for each of the 16 railway zones is shown in Figure 6. The South Central Railway is able to connect the most solar PV generation (625 MW) due to having the highest traction energy demand. The North Eastern Railway has the smallest traction energy demand and therefore is only able to connect 117 MW of solar PV generation.

The true daily demand profile on Indian Railways is expected to lie somewhere between the two modelled Flat and Commuter profiles. For illustrative purposes therefore, the median solar generating capacity that could be directly connected to the traction network in each region is shown on the map in Figure 7.

To understand how connecting solar PV generation would impact the solar PV utilisation and percentage of traction demand supplied another simulation was performed. The average solar PV output as presented in Figure 3 and the total Indian Railways energy demand was used to calculate the solar PV utilisation and percentage of traction demand supplied for 1,000 MW to 50,000 MW of solar PV generation connected to
Indian Railways. The simulation model has not considered any voltage rise or thermal network constraints and it may not be technically possible to connect 50,000 MW to the electrical network. The simulation is based on matching the energy output with the energy demand for every hour of the year. The results show the relationship between solar PV utilisation and the traction energy demand.

Using the average solar PV generation profile and the total energy consumption will lead to different results from modelling each region separately. This is because the average solar generation is not weighted with respect to the location of the traction demand. If the traction demand is in a lower solar resource area, more solar PV generation will need to be installed to meet the same share of the load. If the traction demand is in a higher solar resource area, less solar PV generation will need to be installed. Considering the average will provide a reasonable estimate.

Figure 8 shows the results of increasing the amount of solar PV generation connected to the Indian Railways traction network. It is observed that for low amounts of solar PV generation connected, the solar PV generation has a higher utilisation and can supply more of the traction demand for the flat profile than the commuter profile. As the capacity of the solar PV generation increases, the utilisation and amount of traction demand
supplied converge to approximately 20% utilisation and 55% of traction demand supplied for 50,000 MW of solar PV generation.

A utilisation of 20% means that either 80% of the solar PV generation will be exported at the grid supply point or will need to be curtailed. Even if there are no technical constraints for connecting 50,000 MW of solar PV generation, there is unlikely to be a business case for connecting solar PV generation to the rail traction network where only 20% of the generation could be used by the traction demand.

A more likely commercially viable installation requires more than 80% utilisation of solar PV generation energy where the remaining <20% is either exported at the grid supply point, stored in batteries or curtailed. In this scenario approximately 10,000 MW of solar PV generation could be connected for the flat profile, supplying 42% of the traction demand. For the commuter profile, only supplying 30% of the traction demand with 7,000 MW of solar PV generation would achieve an 80% utilisation.

Indian Railways’ have published a target of 20,000 MW of solar PV generation for both traction and non-traction demand. This report does not consider the non-traction demand, and nor does it consider projected growth in traction demand on Indian Railways over the coming decades. If 20,000 MW of solar PV generation were connected directly to the rail traction system to supply traction demand at current levels, approximately 49% of the traction demand could be supplied at a solar PV utilisation of 47% for the flat profile. For the commuter profile, the traction demand supplied reduces to 45% with a solar PV utilisation of 43%.

Connecting solar PV generation with battery storage will increase the solar PV utilisation and percentage of traction demand supplied.
Conclusions

It is expected that up to 28% of the Indian traction demand could be supplied through direct connection of solar PV generation without significant losses or curtailment. Solar plants where over 99% of the yield is used exclusively by the railway are likely to be very attractive commercially for both developers and Indian Railways. The numbers produced in this report have not considered any specific land constraints to meeting the required solar PV capacity and are provided with the assumption that there is sufficient land area at each site to place the optimum number of panels. However, given that Indian Railways have identified 51,000ha of land suitable for solar development in pursuit of their 20GW PV target, we do not consider land use constraints to be a limiting factor for direct solar-to-rail traction supply.

Connecting more solar PV generation will reduce the percentage of solar PV generation that can be used by the traction demand. Allowing for at least 80% of the solar PV generation to be used by the traction demand increases the potential maximum amount of traction demand that can be supplied to 42% without the use of storage technologies. We therefore estimate that between a quarter and a half of Indian Railways’ planned 20GW of new solar PV generating capacity could be viably connected directly into the rail traction network rather than to the grid in India. This would be likely to deliver substantial system cost savings as India’s distribution and transmission networks’ energy losses are the highest in the world19, with average losses across India’s DISCOMs equivalent to 26% of all electricity generation20. The excess generation will either be exported at the grid supply point back into the Indian electricity network, need to be curtailed or could be used to charge energy storage devices.

Electrifying the rail network and converting diesel trains to electricity will initially increase Indian’s total electricity demand by 1% and CO2 emissions from Indian Railways by 32% (assuming the electricity grid can provide this increase in demand). There is a large increase in CO2 emissions from Indian Railways because India’s electricity generation mix currently has a high percentage of coal generation, accounting for approximately 81% of the total energy generated. Substituting grid supplied traction energy which is predominantly sourced from coal generation with direct supply from renewable sources would reduce the emissions from the electrified rail network.

Direct connection of up to 5,272 MW of solar PV generation will support Indian Railways to meet its net zero carbon emissions targets by 2030; potentially reducing emissions by up to 6,840,875 tCO2e per annum when compared to the baseline of 24,330,493 tCO2 for a 100% electrified railway without connection of renewable generation representing a 28% reduction in CO2 emissions.
