ITES
Part of the UK-India Net Zero Innovation Virtual Centre

Indian Railways Decarbonisation Stakeholder Landscape Report

Progress on renewable energy integration on Indian Railways as of early 2025

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En-genuity

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CATAPULT Energy Systems

Contents

1 The context for decarbonization: IR Net Zero 2030

The Prime Minister of India, during his address to the Nation on 15th August 2021, announced that "Indian Railway has set a target of becoming Net Zero Carbon Emitter (NZCE) by 2030". Further, during COP26 summit at Glasgow he declared "Every year more passengers travel by Indian Railways than the population of the world. This huge railway system has set a target of making itself Net Zero by 2030. This initiative alone will lead to a reduction of emissions by 60 million tonnes annually."

Figure 1: Progress of electrification on IR's railway network, 2023-24 Yearbook[1]

These two statements highlight the importance of decarbonizing Indian Railways (IR) and the urgency to do so. Net zero emissions refers to achieving an overall balance between greenhouse gas (GHG) emissions produced and GHG emissions taken out of the atmosphere. Achieving net-zero can still entail production of some GHG emissions, as long as they are offset by processes that reduce GHG already in the atmosphere.

From IR's point of view, this means that IR needs to rapidly reduce diesel consumption and move to renewable energy (RE) for running its operations – both traction and non-traction. As per the GHG Protocol Corporate Standard, developed by World Resources Institute and the World Business Council for Sustainable Development, emissions of IR can be classified under the 3 categories.

- Scope 1: Direct GHG Emissions - Direct GHG emissions from sources owned or controlled by the company (such as diesel fuel consumption in locomotives)
- Scope 2: Electricity Indirect GHG Emissions - Emissions from the energy purchased from third parties (such as generation of electricity for traction)
- Scope 3: Other Indirect GHG Emissions - Emissions from sources not owned or controlled by the company (such as upstream emissions from steel production for tracks and masts etc.)

IR's Net Zero 2030 target is focused on reduction of Scope 1 and Scope 2 emissions.

[1] Indian Railways Year Book 2023-24, Indian Railways Statistical Publications, Ministry of Railways, New Delhi

2 Background

- **Riding Sunbeams Apollo Ltd**

- Riding Sunbeams has been working on overcoming the barriers to direct wire supply from solar to railways since 2017 (before the current company was incorporated). Over the last six years we have worked closely with Network Rail, Transport for Wales and Transport for London on a range of innovation projects exploring different dimensions of this challenge, including developing and demonstrating a connection methodology for DC third rail traction networks just outside Aldershot station, and developing designs for the bespoke power electronics interface needed to connect to AC overhead lines.

- We have also worked extensively with our major shareholder Thrive Renewables to develop the business case for financing solar traction farms through long-term Power Purchase Agreements with the railway end-users, including forming a comprehensive understanding of optimal traction network conditions for injecting solar energy, sizing of schemes, and interactions with the grid at rail bulk supply points.

- Since 2024 we have been working with the Catapult to adapt their local area energy planning tool to enable partial automation of solar PV site prospecting for private wire traction supply to railways; and with traction power specialists EneRail to develop high-level traction demand modelling capabilities for individual routes and line sections. We will shortly be applying this learning to a feasibility study with the Indian Institute of Science in Bangalore to assess the potential for solar to directly power the new Blue Line on the Bangalore Metro.

- Our 2021-22 feasibility study into the potential for solar direct wire supply to Indian Railways found that around 25% of IR's traction load could be met in this way on commercially attractive terms, a share that could increase with the integration of energy storage solutions[2]. While India has made astonishing progress on rail electrification in recent years, and is now almost 100% electrified, its coal-dominated grid means solar traction power substitution also yields much greater per-kWh CO2 emissions reductions here than in the UK and Europe. India is the best place in the world for solar rail and we want to be part of making this happen at scale.

- **En-genuity**

- Set up in 2018, En-genuity is a New Delhi-based consultancy with extensive experience in the areas of energy and climate change, clean & distributed energy, sustainable development, policy and regulatory analysis in the energy domain, efficient use of energy, resource efficiency, marketing research, strategy, performance optimization & excellence, financial analysis and modelling.

[2] R*iding Sunbeams in India: Indian Railways' net-zero commitment is key to India's decarbonisation*, 2022, Riding Sunbeams, Climate Trends and Ricardo EAE

- The promoters of En-genuity, before the organization was established, had worked with Indian Railways (IR) in promoting solar rooftop projects across its various establishments like railway stations, station and office buildings, etc with much success - more than 120 MW of solar rooftop projects have already been installed in IR premises.
- En-genuity has been working with Indian Railways (IR) on renewable energy initiatives since the company was founded.
- **Our partnership**
- The ITES programme has created an important opportunity for Riding Sunbeams and En-genuity to collaborate to bring solar rail solutions to fruition in India over the coming years, and we have signed an MoU committing us to achieving this.

3 India's railway network electrification, climate commitments and energy independence imperative

World-beating railway network electrification

Indian Railways (IR), one of the world's largest railway networks with 69,181 km of route length, consumes a substantial proportion of India's total electricity and diesel usage, rendering it a significant factor in the country's transition to a low-carbon economy. In recent years, IR has markedly accelerated its electrification efforts, both in terms of network expansion and daily electrification rates. The chart below shows the increasing pace of electrification, underscoring the strategic initiative towards achieving 100% electrification by FY 2025-26 . The unprecedented speed of India's rail electrification works is put into perspective when compared with the UK. During Network Rail's five year Control Period 6 between 2019-2024, electrified route kilometres on GB railways increased by just 118km, versus electrification of nearly 28,000 route kilometres of Indian Railways' network. In 2022/23 alone Indian Railways electrified more new route kilometres than the UK's entire electrified network put together[3].

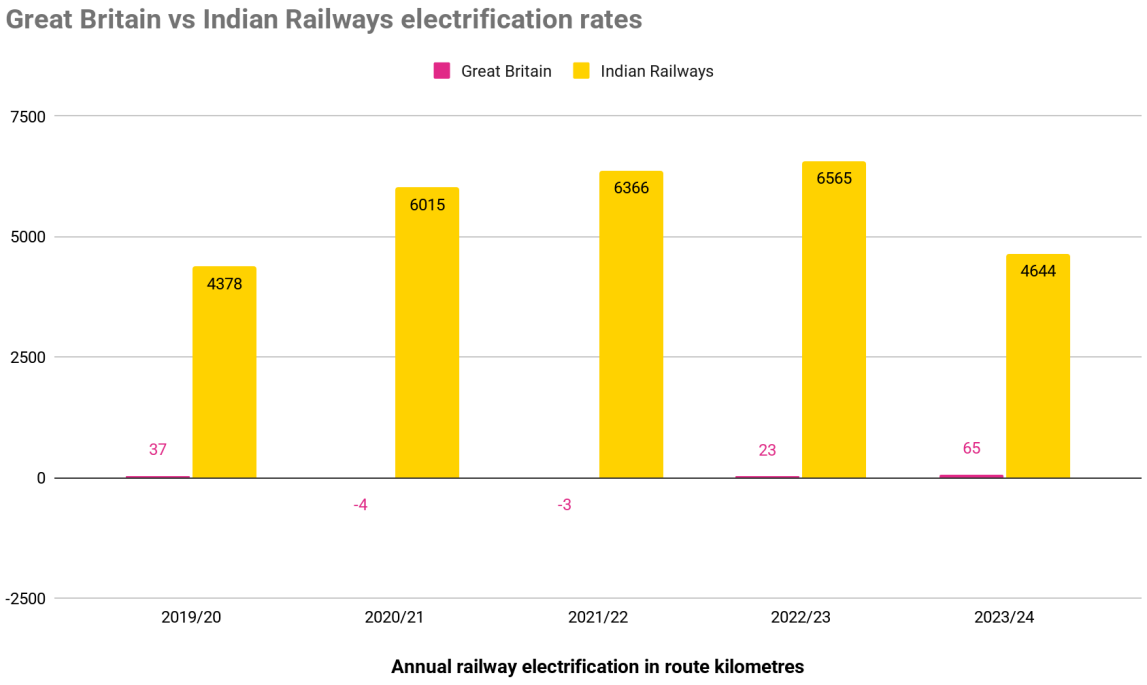

Figure 0: Great Britain vs Indian Railways electrification rates 2019-2024

Looking around the world, only Switzerland (a rich country with abundant hydropower and no domestic sources of hydrocarbon fuels) has achieved 100% of network electrification.

3 https://indianrailways.gov.in/railwayboard/uploads/directorate/ele_engg/RE/2024/Railway%20Electrification_final.pdf / Rail infrastructure and assets, October 2024 Office of Rail and Road statistical release https://dataportal.orr.gov.uk/statistics/infrastructure-and-environment/rail-infrastructure-and-assets/

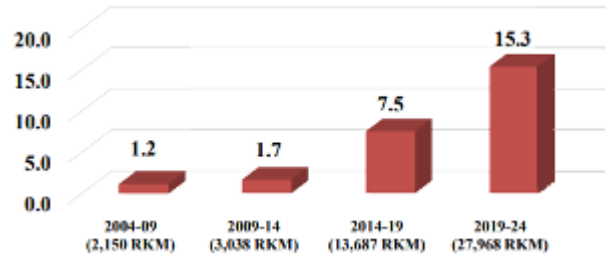

Figure 1: Growth in electrification

Rising consumption and the need to reduce energy costs

One of the primary drivers behind IR's push for electrification was the rising cost of diesel and the import dependency of the country on the same. With falling cost of and renewable energy (RE) IR began to explore large-scale adoption of solar and wind energy into its operations. The move toward electrification and direct renewable energy procurement was seen as a cost-saving measure to reduce dependency on fossil fuels and stabilize long-term energy costs, part of Prime Minister Modi's wider national 'Atmanirbhar Bharat' or 'self-reliant' India economic mission which aims to make India energy independent by 2047. India currently imports almost 90% of its oil.

In common with Network Rail and Transport for London in the UK, more than 85% of IR's electricity demand is for traction purposes, with the remainder being consumed at stations, office complexes and other buildings and infrastructure owned by the railways.

IR's projected electricity consumption is set to increase from 21.3 TWh in 2016 to 48.7 TWh by 2030[4], with traction power forming the bulk of this growth as network electrification and new high speed rail and dedicated freight corridor routes come online.

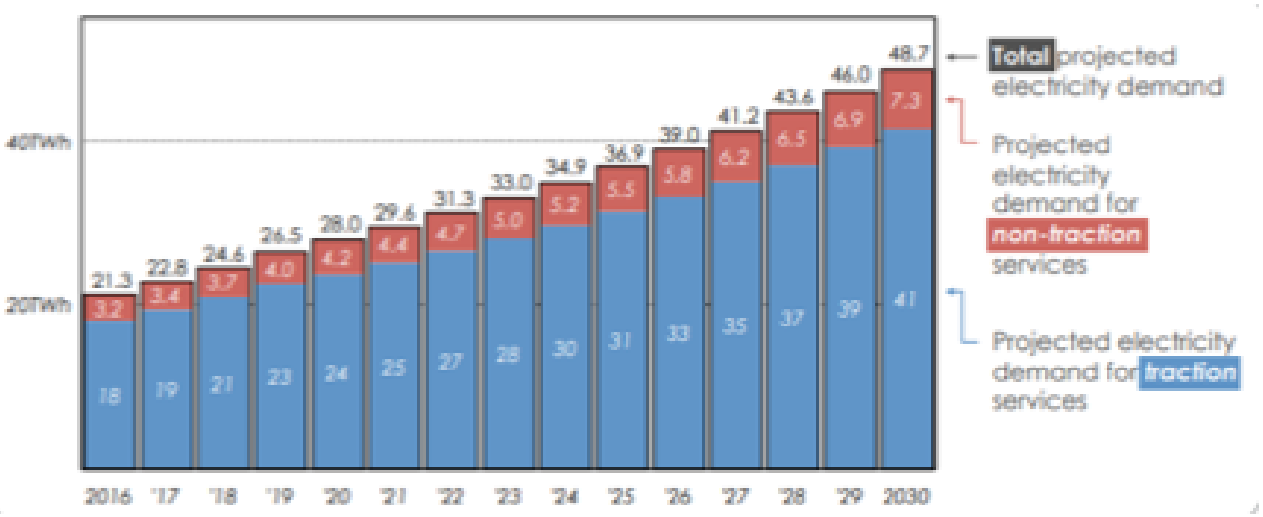

Figure 1: Projected energy consumption of IR

Figure 3: Projected energy consumption of IR

[4] Climate Policy Initiative (CPI) analysis

This steep rise underscores the need for a stable, cost-effective, and sustainable energy supply: meeting IR's 2030 electricity demand will require a roughly 1% increase in India's electricity generation. Without transitioning to large-scale direct renewable energy procurement, the growing reliance on fossil fuel-based electricity could exacerbate cost burdens and environmental impacts. The shift toward solar, wind, and hybrid power sources is not just a decarbonization strategy but an economic imperative to mitigate escalating energy expenses and enhance long-term financial sustainability for IR.

Importantly, in 2021 Riding Sunbeams' calculated that IR switching its entire fleet from diesel to electric power would initially lead to a substantial increase in carbon emissions of around 32% . Indian grid supply emissions are over three times higher per unit of electricity than grid supply emissions in the UK because of the much higher percentage of coal generation on the Indian electricity system. Therefore while full network electrification is necessary to decarbonise Indian Railways' operations, it is not at all sufficient[5].

[5] *Riding Sunbeams in India*, 2022, Riding Sunbeams, Climate Trends and Ricardo EAE

India's Climate Commitments & Policy Shifts

India's commitment to reducing greenhouse gas (GHG) emissions has been a major policy driver for IR's decarbonization efforts. Under the Paris Climate Agreement (2015), India pledged to:

- Reduce emissions intensity by 45% (from 2005 levels) by 2030.
- Achieve 50% of its total installed power capacity from non-fossil fuel sources by 2030.
- Transition key sectors, including railways, to green energy sources.

As a high-emission sector, Indian Railways was identified as a priority area for electrification and renewable energy integration. Aligned with India's national climate commitments, Indian Railways (IR) has undertaken a decisive transition towards decarbonization, setting a target to achieve net-zero carbon emissions by 2030. This objective is not merely an extension of India's pledge under the Paris Agreement but a strategic necessity to mitigate fossil fuel dependency, enhance energy security, and optimize long-term operational costs.

As one of the largest consumers of electricity and diesel in the country, IR recognizes that maintaining the status quo would result in escalating emissions, higher energy expenditures, and increased reliance on imported fuels. To address these concerns, IR has implemented a structured electrification and renewable energy strategy, emphasizing full network electrification, large-scale integration of renewable power, and efficiency improvements.

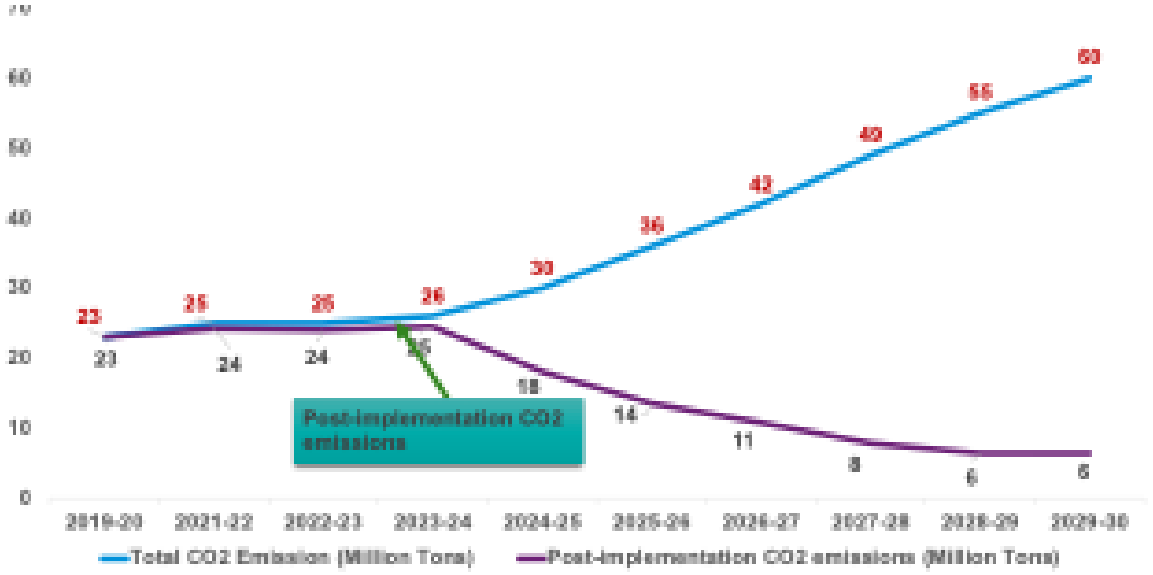

Figure 4: Projected emission trajectory of IR till 2030

Falling renewable energy tariffs

Between 2015 and 2025, solar and wind energy prices fell dramatically in India, making renewables a viable and cost-competitive alternative to traditional electricity sources. While in 2015, solar power tariffs were in the range of Rs 5 to 6 per kWh, it has come down to around Rs 3 to 3.5 per kWh in 2023-24. Wind tariffs have also come down. The pivotal year was 2020 when the tariff reached Rs 2 - around 2 pence - per kWh[6].

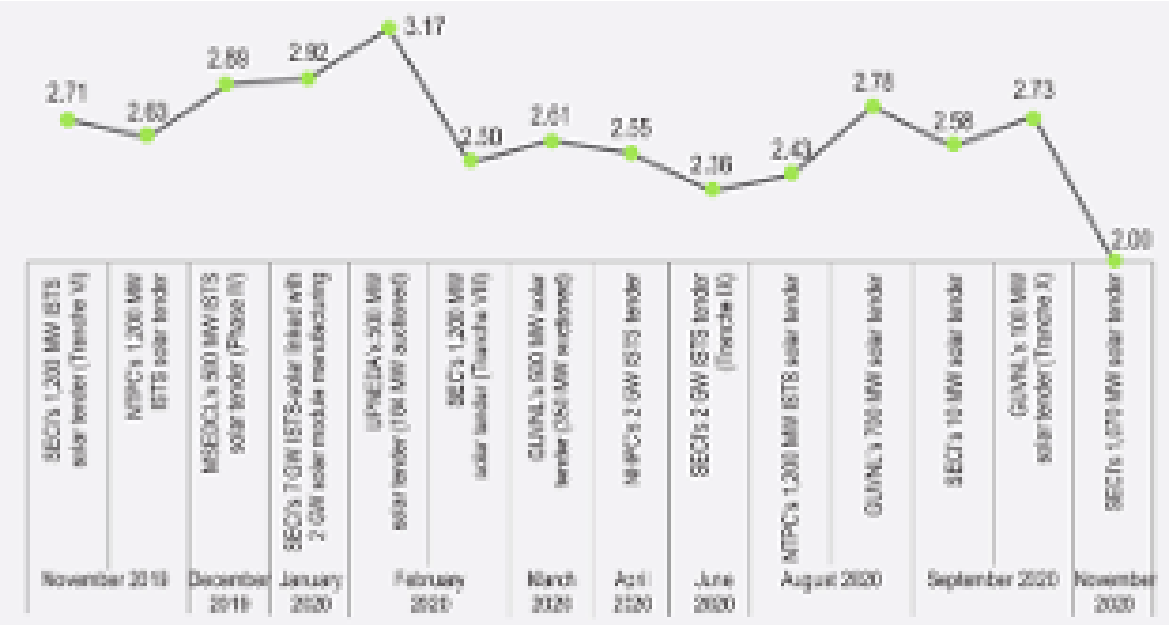

Figure 5: Solar tariffs discovered in 2020 through Government auctions

Such low prices, coupled with advancements in energy storage solutions and grid integration technologies, have made large-scale renewable energy procurement an attractive option for Indian Railways. The Indian government has consistently emphasized energy security as a strategic priority. Given the volatility of global fuel markets, reducing reliance on imported diesel and coal-based power became a core objective for Indian Railways.

Electrification, coupled with domestically produced solar and wind energy, has helped enhance India's energy security while also reducing foreign exchange expenditures on fuel imports.

[6] Renewable Energy Watch research (https://renewablewatch.in/)

4 Renewable energy use by Indian Railways

Key RE initiatives undertaken by IR

IR has already started adopting renewable energy (RE) in its operations, for both traction and non-traction demand. As of March 31, 2022, IR had achieved a total installed capacity of 243 MW with an expected reduction in carbon emission of up to 300 thousand tonnes per annum. In FY 2020-21, IR developed a RE plan till FY 2029-30 as part of its Net Zero Carbon Emission (NZCE) Action Plan.

Based on past energy demand growth rate, expected electrification rates and traffic increases, demand to FY 2029-30 had been projected. Annual RE installed capacity targets are identified to meet the projected energy demand. As per the projections, renewable energy capacity of 30 GW would be needed by 2030, which entails an investment of Rs 1.5 lakh crore. RE procurement plans will be implemented mostly in Developer Mode, in which capital investments (and associated risks) will be undertaken by third parties, with IR buying renewable electricity generated from developers through power purchase agreements (PPAs). Selection of the parties is based on reverse auctions to achieve the lowest cost tariffs, in line with typical Indian public sector 'L1' - 'lowest one' - procurement practice.

IR plans to procure the majority of their 30GW RE capacity power requirement through RE-based 'Round the Clock' (RTC) Mode tenders supplying 24x7 power for a specified number of days in each year. Under this model renewable energy developers develop RE projects and tie up with balancing power sources (such as pumped hydro plant) to supply RTC with renewable electricity as per the supply requirement[7]. Power procurement for IR is led by the Railway Energy Management Company Limited (REMCL), a joint vehicle of the Rail Ministry and RITES set up with the sole purpose of sourcing energy for Indian Railways, and now largely responsible for meeting IR's 2030 net zero target through sourcing of RE.

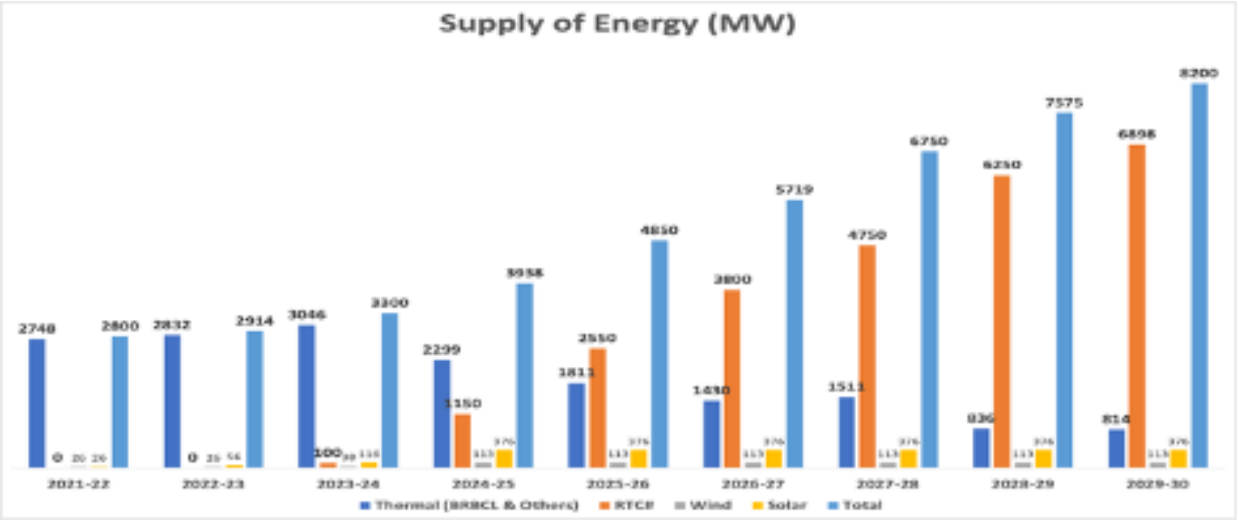

Figure 6: Planned supply till 2030 in megawatt (MW) peak installed generating capacity

[7] IR's NZCE Plan

Timeline of key IR RE initiatives

Table 1: Key decarbonization initiatives of IR

Initiatives	Implementing Agencies	Start Year	Target Year	Achievement
1 GW Solar Energy Target announced for Indian Railways	Ministry of Railways	2015	2020	100%
Mission 41K launched to save INR 41,000 Cr in energy costs over 10 years.	Ministry of Railways	2016	2025	67% (Significant savings achieved, as per CAG audit)
Open Access electricity procurement initiated in select states	REMCL, Private Energy Producers	2015	ongoing	Continuous process
RTC power procurement	REMCL, Divisional Railways, private developers	2020	2030	> 1,700 MW
Bina Solar Traction Pilot Project launched (1.7 MW) and 2 MW at Diwana	West Central Railways and Northern Railways, private developer	2020	ongoing	Successful, expansion required
Station rooftop solar program	REMCL, Divisional Railways, private developers, DISCOMs	2017	ongoing	More than 250 MW has been installed

As of February 2025, Indian Railways' renewable energy procurement activities had already led directly to over three quarters of a gigawatt of new renewable energy capacity being commissioned.

Renewable power capacities commissioned	
Solar (Rooftop + Land)	553 MW
Wind	103 MW
RTC (Round The Clock) (Hybrid- Solar+wind)	100 MW
Total	756 MW

Table 2: Renewable power capacities commissioned under contract to Indian Railways, February 2025[8].

[8] "Indian Railways Accelerates Towards Net Zero Carbon Emissions with Electrification and Renewable Energy Initiatives", Ministry of Railways press release, 21st March 2025 https://pib.gov.in/PressReleaseIframePage.aspx?PRID=2113871

Decarbonization efforts in urban Metro Rail networks

While IR is progressing in electrification and renewable energy adoption, urban metro networks have demonstrated a more expeditious transition due to favorable regulations, streamlined financing, and a smaller operational footprint. Their agility in implementing energy-efficient measures has positioned them as early adopters of decarbonization strategies.

Metro systems in Delhi, Mumbai, Bangalore, Chennai, Hyderabad, and Pune exclusively utilize electric traction, inherently reducing emissions in comparison to diesel-based rail operations. However, their primary decarbonisation gains are derived from renewable energy procurement and efficiency enhancements.

The Delhi Metro Rail Corporation (DMRC) has emerged as a global leader, becoming the first metro system to obtain carbon credits under the UN Clean Development Mechanism (CDM). Its initiatives encompass procuring over 100 MW of solar power via a sleeved PPA with the Rewa Ultra Mega Solar park (RUMSL) which now powers over 60% of DRMC's daytime energy use, implementing regenerative braking to recover energy, and deploying rooftop solar installations across 50 stations. Riding Sunbeams visited DMRC's first of a kind linear trackside solar PV installation at Okhla Vihar in late 2024, where 100kW of bi-facial solar modules are being mounted on each side of the railway viaduct. Yield from the array will supply station load with any surplus going for export, but this approach could be used to feed traction demand in future.

Figure 7: DMRC's trackside vertical solar pilot under construction, November 2024. Photo credit: Riding Sunbeams.

Mumbai Metro is targeting 60% of its electricity from renewable sources by 2027, integrating solar and wind energy while enhancing efficiency through LED lighting and smart energy systems. Bangalore's Namma Metro has already installed 3 MW of rooftop solar at stations, with plans to increase capacity to 10 MW by 2027.

While metro networks operate on a smaller scale than IR, their ability to swiftly adopt green energy solutions can serve as a model for nationwide railway decarbonization.

Institutional stakeholders and their roles

Decarbonizing Indian Railways is a multi-agency effort, requiring the collaboration of government ministries, regulatory bodies, and specialized railway energy agencies. These stakeholders play distinct but interconnected roles in implementing green policies, securing funding, and overseeing execution.

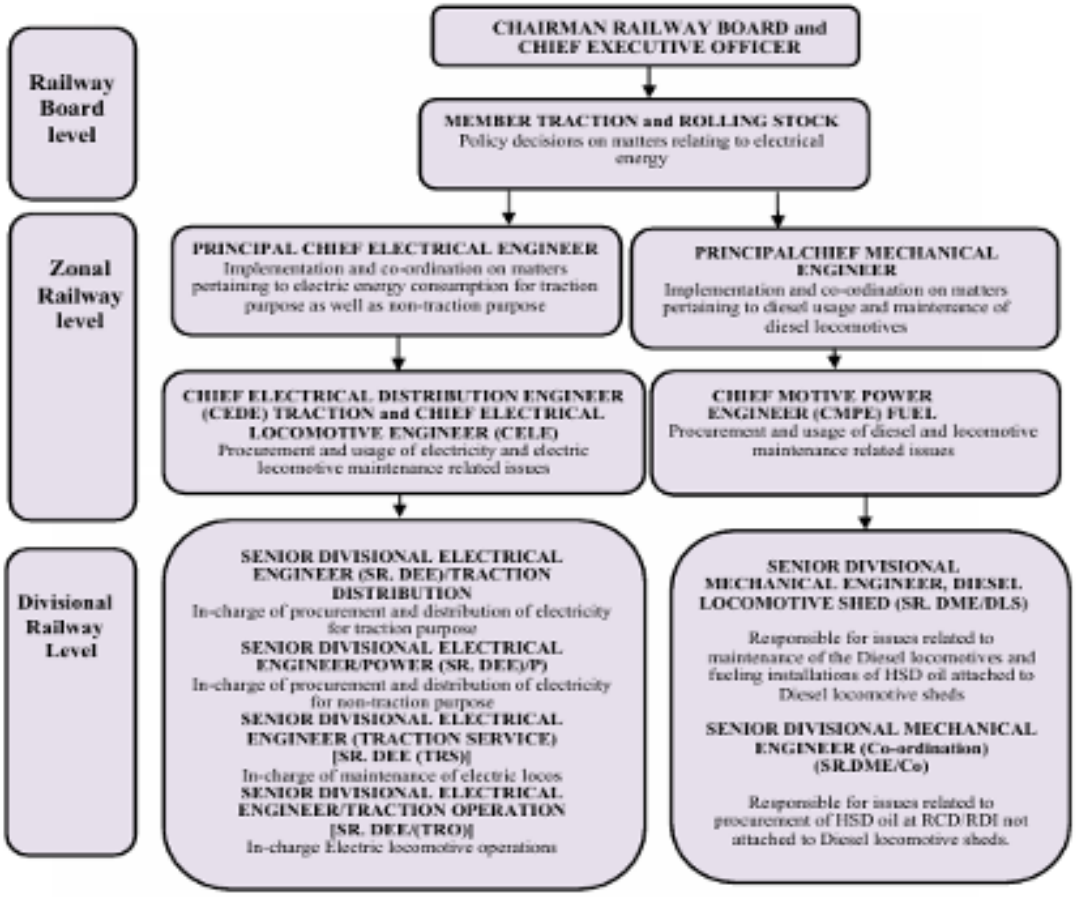

Figure 6: Institutional structure of IR

The Ministry of Railways (MoR) is the apex body responsible for setting the vision for railway electrification and decarbonization. Key responsibilities of the Ministry include:

- Defining energy policy and Net Zero Carbon Emission targets for IR
- Allocating budgets for renewable energy projects
- Overseeing public-private partnerships (PPPs) to fund large-scale solar and wind energy projects.

Railway Energy Management Company Ltd (REMCL) is a joint venture between the Ministry of Railways and RITES Ltd. and serves as the nodal agency for energy procurement, including RE, for Indian Railways. Its responsibilities include:

- Managing power purchase agreements (PPAs) with solar and wind developers.
- Overseeing station rooftop solar installations and direct-wire traction supply projects.
- Negotiating open access electricity purchases to reduce reliance on coal-generated power.

Research Designs & Standards Organisation (RDSO) plays a crucial role in standardizing and upgrading the railway technologies and systems. It is responsible for research, design, and development of new technologies and solutions to improve the efficiency and safety of the railway network.

Divisional Railways, which are part of the Railway Zones, are the stakeholders at the lowest level, but the most important as all interventions are undertaken at their level and their cooperation and support is needed for successfully designing and implementing interventions. Division Railways are also likely to be the contractual counterparties to any direct power purchase agreements with new RE generators.

Indian Railway Finance Corporation (IRFC) is the nodal agency set up to borrow funds from financial markets to support IR investment. In January 2025 IRFC signed an MoU with REMCL to collaborate on financing renewable energy projects awarded by REMCL for supply to Indian Railways[9].

While IR and its agencies develop and execute plans for decarbonization, certain outside stakeholders play crucial roles in dictating or deciding whether such goals are met or not. State Electricity Regulatory Commissions (SERCs) are such key stakeholders. SERCs ensure that the electricity market operates fairly and efficiently within their respective states, which directly affects the cost and reliability of electricity for Indian Railways. Interstate regulations are drafted by the Central Electricity Regulatory Commission (CERC).

9 https://www.business-standard.com/markets/capital-market-news/irfc-edges-higher-on-inking-mou-with-remcl-125010300317_1.html

Institutional and Multi-Stakeholder Challenges

Despite IR's strong commitment to decarbonization, institutional inefficiencies and fragmented regulatory frameworks continue to impede progress. The absence of uniform electricity regulations across states complicates open-access renewable power procurement, delaying project implementation. Moreover, lengthy approval processes for railway electrification contracts and renewable energy projects further slow execution, creating cost overruns and inefficiencies.

Financial constraints present another significant challenge, particularly in securing funding for advanced storage solutions and large-scale renewable energy integration. While private sector participation has increased, smaller renewable developers struggle with capital access due to high upfront investment requirements and limited financing options. Additionally, grid integration issues persist, particularly in states with weak transmission infrastructure, affecting the stability of renewable energy supply for traction operations.

The electricity sector in India falls under the Concurrent List[10] and the SERCs decide on the tariffs at which IR purchases electricity from the DISCOMs, for both traction and non-traction purposes. In cases where IR purchases electricity directly from remote generators through Open Access, charges can be levied by the SERCs for such consumption within their respective state boundaries. Until recently as many as 13 large states had considered IR as a deemed distribution licensee, which enabled IR to procure electricity from third-parties without having to pay a remediation fee for demand defection to the DISCOMs. This status is now subject to legal challenge. If the matter is not resolved in IR's favour, procuring electricity through sleeved PPAs with remote generators will become more expensive[11]. Conversely, this could improve the competitiveness of direct wire supply to their traction system.

Addressing these barriers requires a structured approach to regulatory harmonization, expedited approvals for energy projects, and enhanced financial support mechanisms. Strengthening coordination between state regulators, private energy developers, and multilateral financing institutions will be critical in ensuring IR achieves its decarbonization goals efficiently and sustainably.

[10] The Concurrent List is a vital part of the Indian Constitution's Seventh Schedule, which delineates the distribution of legislative powers between the Union (central) government and the State governments. It encompasses a range of subjects, including education, forests, marriage and divorce, adoption, succession, trade unions, electricity, economic and social planning, etc.
[11] See e.g. https://www.cercind.gov.in/2024/ROP/155-MP-2022Ors._150324.pdf

Outlook for Key Renewable Energy Work streams

IR has made remarkable strides toward integrating renewable energy into its operations. However, to meet its Net Zero Carbon Emissions by 2030 goal, three key renewable energy work streams have been identified as essential areas of focus:

- Station rooftop solarization
- Corporate sleeved power purchase agreements (PPAs)
- Direct wire traction supply

Each of these work streams plays a distinct role in increasing Indian Railways' renewable energy capacity, improving energy efficiency, and reducing dependency on fossil fuels.

Station Rooftop Solarization

Figure 8: Rooftop solar PV at Agra Cantt Station, December 2024. Photo credit: Riding Sunbeams.

Rooftop solar installations at railway stations and administrative buildings are one of the most straightforward and cost-effective ways for IR to increase self-generated renewable power, off-setting its consumption from DISCOMs for non-traction use, the tariffs for which are comparatively higher as compared to traction tariffs. Switching to solar energy is expected to reduce 6.85 million tonnes of CO_2 emissions annually, in addition to the 15 million tonnes from railway electrification. As of January 2025, Indian Railways has installed 500 MW of rooftop solar capacity, covering over 1,000 stations.

Several key milestones have been reached:

- Delhi, Mumbai, and Chennai railway stations now generate 30% of their energy needs from rooftop solar installations.
- More than 110 railway workshops and administrative offices have been equipped with solar panels.
- Plans are in place to increase the capacity to 1 GW by 2027, with an emphasis on including smaller, regional stations.

Despite its success, station rooftop solarization faces several hurdles, including:

- Intermittent energy generation: Since solar energy is weather-dependent, energy storage solutions like battery integration need to be developed to achieve high penetration rates of RE in IR's supply mix.
- Regulatory barriers: Some states lack clear policies for net metering, slowing project approvals. Further, DISCOMs are generally not keen in providing inter-connectivity to solar rooftop projects, as these result in loss of revenue – IR pays bills on time.
- Financing issues: IR has relied on private investment and public-private partnerships (PPPs) to expand rooftop solar, but additional incentives may be needed to attract more private players.

By 2027, Indian Railways aims to generate 15-20% of its total energy needs from rooftop solar. Increased private investment will drive expansion, with newer Build-Own-Operate-Transfer (BOOT) contracts being introduced. Hybrid solar + battery storage projects will be tested at key railway stations to improve energy stability.

Corporate sleeved PPA

Corporate Sleeved PPAs serve as a critical mechanism for IR to secure cost-effective renewable energy without direct ownership of generation assets, and as in the UK, are expected to be the principal method by which railways meet their renewable energy targets. These agreements facilitate power procurement from independent renewable energy developers through an intermediary utility, ensuring a stable and predictable energy supply. By the start of 2025, IR had already secured ('tied up' in the Indian parlance) over 1.5GWp of RE capacity, primarily through sleeved PPAs with new generators, including 4,260 MW of installed solar capacity and 3,427 MW of installed wind capacity. At the end of February 2025, IR's West Central Railway Zone contracted with RUMSL for a further 170MW of solar at a record low price of Rs 2.15/kWh.

The structured approach to corporate PPAs is categorized into three primary segments:

- Solar PPAs: IR has prioritized solar power procurement due to its declining costs and widespread availability. Several long-term solar PPAs have been executed, allowing IR to procure energy at competitive tariffs through direct agreements with developers. This model has enabled IR to secure a reliable supply while benefiting from lower tariffs driven by reverse bidding auctions.

- Wind PPAs: wind energy procurement has been integrated into IR's renewable energy portfolio to complement solar power, particularly during non-daylight hours. Wind PPAs offer the advantage of higher capacity utilization factors (CUF) in specific geographies, balancing seasonal variations in solar generation. IR is strategically engaging with wind power developers in states with favorable wind energy policies and infrastructure.

- Round-the-Clock (RTC) PPAs: to ensure a continuous and stable power supply, IR is transitioning towards RTC PPAs, which combine solar, wind, and energy storage solutions. These agreements, each of which brings in excess of 100MW of capacity, are structured to maintain a minimum guaranteed power availability,

optimizing the share of RE supply to meet IR's traction and non-traction energy needs. RTC contracts also mitigate the intermittency challenges of standalone renewable sources, improving grid stability and reliability. Per kWh prices returned for these huge tenders have been as low as Rs 3.5.

There are, however, certain challenges with respect to sleeved PPAs. Inconsistencies among central and state regulations, including open-access tariffs, wheeling charges, cross-subsidies and surcharges, etc and lack of policy certainty in the long term are some of the regulatory barriers that IR is facing. The success of sleeved PPAs is also dependent on the evacuation infrastructure, which needs to keep pace with the speed at which large-scale RE projects are being set up. Recently, this has become a constraint.

Incorporation of energy storage is imperative in RTC procurement contracts, and energy storage is expensive. The additional cost of storage is reflected in the final tariff and can act as a barrier. There is some indication that the early RTC contracts have partnered with pumped hydro providers, which is much less expensive than Battery Energy Storage Systems (BESS) but is a finite national resource with long development lead times that relies on suitable topological, geological and hydrological conditions. As this 'low hanging fruit' is picked, the increasing need to rely on higher cost BESS for balancing is likely to impact PPA prices.

Finally, as more and more RTC power is procured by IR, the overall supply curve will reach close to the overall demand curve. As the demand curve is not a straight line – it has its crests and troughs – RTC procurements at that stage will have to be designed according to time blocks, which will increase the overall tariff, maybe drastically.

Direct wire supply

Direct wire traction supply refers to renewable energy plants that directly power railway operations without passing through the national or state transmission networks. This system provides a more efficient and cost-effective energy supply by eliminating transmission losses (and system costs) and reducing reliance on coal-based grid power.

One of the biggest breakthroughs in IR's decarbonization journey was the Bina Solar Traction Pilot Project, launched in Madhya Pradesh in 2019. This 1.7 MW solar plant is connected at an IR traction substation, directly powering trains along a key route, which has demonstrated the technical feasibility of scaling direct renewable traction energy supply. In the same year, IR expanded its direct wire solar project to Diwana, Haryana where a 2 MW solar plant has been set up. This plant, however, feeds the solar electricity to IR's own 132kV transmission line connecting a few traction substations (TSSs) in the region.

While direct wire traction supply holds immense potential, it faces technical and financial challenges:

- **Lack of appropriate inverters/ converters:** the converters used in the Bina pilot are not commercially available in the market, as there is currently no demand for large capacity single phase converters. Further, this converter design is not fully bi-directional, limiting its potential use cases, e.g. Battery Energy Storage System (BESS) integration. An appropriate converter, thus, needs to be designed and

manufactured at a commercial scale, but power electronics manufacturers may need sight of significant demand for such a product before they will invest in the up-front development and NRE costs and manufacturing capacity. The 'Daybeak' converter Riding Sunbeams has co-developed with Network Rail and Turbo Power Systems to fulfil this use case in the UK and European markets would be technically suitable, but is likely to require substantial redesign to optimise costs (as well as find a volume manufacturing partner in India) to succeed commercially in the Indian market.

- **Land availability issues:** unlike rooftop solar, land-based solar plants require significant space, making land acquisition a bottleneck. Utilizing railway-owned land can help overcome this, and IR is India's second biggest landowner with substantial holdings around substations and depots as well as the rail corridors themselves. A further challenge for rail-adjacent sites in India is the prevalence of often large communities of squatters who have set up makeshift homes on railway land.

- **Financial attractiveness:** direct wire supply projects need to be structured 'well' so that private parties find them attractive to invest, and IR finds them attractive to procure. Proper site assessments, making technology available and clustering of projects may be undertaken. Certain features of India's electricity economy and the regulations that govern it also factor: IR's deemed licensee status discussed above currently enables it to avoid DISCOM fees for remote sleeved PPAs, and the ongoing national RE exemption from Inter-state Transmission System (ISTS) fees favours long-distance power procurement by removing part of its delivery cost from the price paid per kWh by the customer. These are two market distortions that make it artificially challenging for private wire supply from lineside generators to compete with sleeved supply from large, remote wind and solar projects. The ISTS waiver is due to be phased out altogether by 2028.

- **Market readiness:** a hasty attempt by REMCL to tender for around 1.5GW of solar for direct wire supply to IR substations in 2022 failed to attract bids, in part because the Indian solar developer sector has few companies that specialise in building single-digit MW scale solar parks as opposed to India's thriving rooftop solar sector or the very large utility scale developers building plant of 100s of MWs capacity. Some market priming in India's solar sector may be needed to ensure the supply chain has the necessary capacity and expertise to fulfil a rollout of direct wire solar traction schemes on India's railways.

5 The future: new Indian rail decarbonization opportunities

While Indian Railways has made tremendous progress in electrification and renewable energy adoption, new opportunities are emerging to accelerate its Net Zero transition.

High-Speed Rail (Bullet Train) & Green Energy Integration

The Mumbai-Ahmedabad Bullet Train project (India's first high-speed rail system) is expected to consume large amounts of electricity. If this power is sourced from renewable energy, it could set a global precedent for green high-speed rail. Key RE integration plan for this corridor include:

- Railway stations along the corridor will be 100% solar-powered.
- Dedicated solar and wind farms will be developed to offset energy demand.
- Energy storage solutions will be integrated to maintain stable power supply.

Dedicated Freight Corridor (DFC) Expansion

Freight corridors are among the most energy-intensive railway operations, but full electrification of DFCs can drastically cut emissions. The Eastern DFC and Western DFC are on track to be 100% electrified by 2026. DFC is exploring direct renewable energy procurement to reduce costs.

Metro Rail Expansions

As India's urban population grows, metro rail networks are expanding rapidly. New metro projects are integrating renewable energy from day one, setting a benchmark for sustainable public transit. Key future developments include:

- Chennai, Bangalore, and Hyderabad metro expansions include station-based solar projects.
- New Metro rail corridors in Pune, Surat, and Patna are designed to be fully electrified with clean energy sources.

Way forward

With 100% electrification set to be achieved in 2025-26 (IR was at ~97% at the end of 2024), IR plans to run a major and growing portion of rail traffic through electric traction, with diesel locomotion being rapidly phased out of operation. Presently, the majority of IR's traction electricity is being sourced from thermal generation sources. IR is planning to progressively shift from thermal to RE sources to achieve NZCE. To deliver NZCE by 2030, IR has adopted a four-pronged strategy.

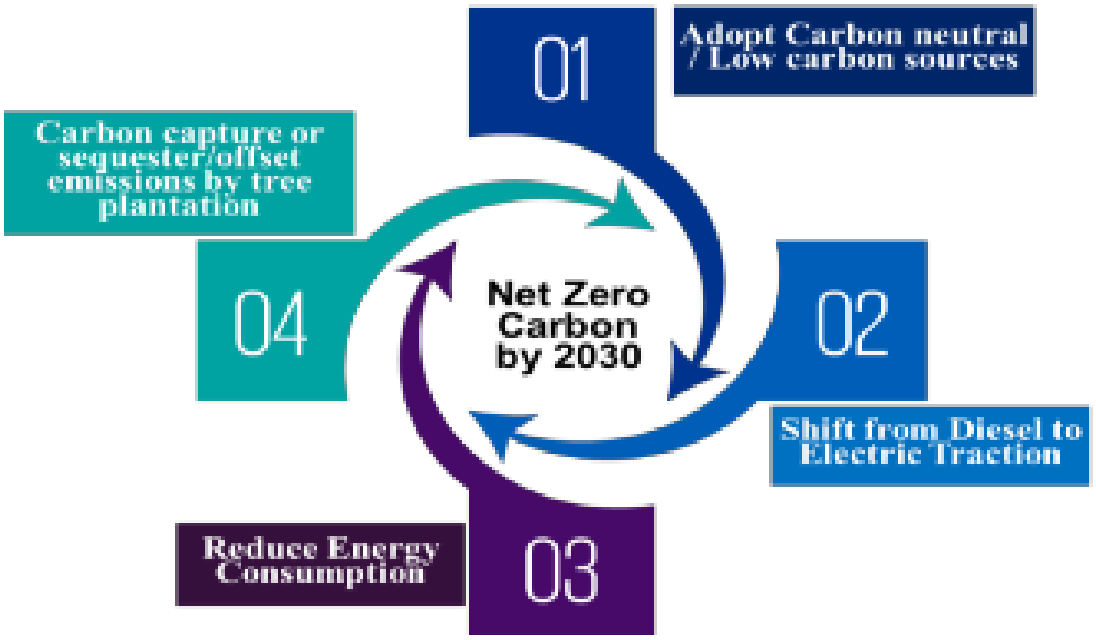

Figure 10: IR's Net Zero strategy

Keeping its demand profile in consideration, IR has stopped preferring plain 'vanilla' solar or wind procurements. Over the past three years, its focus for large-scale power procurement has shifted to 'Round The Clock', (also 100% RE based), as RTC PPAs offer a better power generation profile and smoother output. However, lack of long term policy direction, uncertainty on its deemed licensee status and potential increase in tariffs in future will make RTC procurements more and more expensive.

IR has had a positive experience on direct-wire supply – the Bina project. This successful 1.7MW scheme provides technical proof of concept for solar to feed IR's 25kV AC traction system. The next step is to demonstrate that IR can procure low cost solar power commercially from lineside third party generators at this scale. With its network spread across the country and ownership of land on both sides of the tracks, the potential for direct-wire solar supply schemes to be hosted on IR's estate is immense.

A study conducted by UNDP, of which one of the authors of this paper was the lead consultant, assessed a potential of at least 1 GW for this technical architecture. Looking beyond IR's own land and property portfolio, Riding Sunbeams' 2021 study estimated that up to 5GW of new solar capacity could be connected to the IR network nationally on commercially attractive terms for both developers and railways - enough to meet around 25% of IR's total traction electricity demand.

A key challenge is the commercial availability of large-capacity single phase inverters. Drawing from the specifications of the Bina pilot, and Riding Sunbeams' work on a similar engineering solution for the UK, an updated design with two-way flow of electricity, should be accorded priority and projects should be structured around this solution. This can be a significant contributor to IR's Net Zero target.

Next steps for Riding Sunbeams in India

- Riding Sunbeams is working with the Indian Institute of Science in Bangalore to develop a feasibility study to explore the potential to integrate direct wire solar supply to meet traction demand on Namma's under-construction Blue Line to Bangalore airport. If the study finds in favour, the next step will be to deliver a MW-scale pilot project to help power the new line - a first of a kind for Indian metros.

- We will liaise with REMCL to develop a 20-50MW commercial pilot programme for private wire solar supply to Indian Railways, building on the Bina demonstrator's technical success to prove that this approach to traction energy procurement can be commercial successful too. Early indications point to working with three or four individual Railway Zones to identify a portfolio of host sites for PV on Indian Railway land around selected high-demand traction substations.

- Concurrently, we will look to develop a partnership with a suitable Indian power electronics manufacturer with a strong track record of supplying India's rail sector, and work with them to identify and secure funding to develop a cost-optimized, fully bi-directonal single phase inverter solution to enable the solar-to-traction value proposition to be rolled out at scale on Indian Railways' 25kV AC traction power networks. We will also scope the potential to produce this low-cost connection solution in India for export to rail clients in the UK, Europe and beyond.

- We will also assess transferable learning from our recent market research into DC traction-integrated rapid response energy storage technologies (supercapacitors and flywheels) on metros and light rail systems; and our upcoming SIF-funded work with the Energy Systems Catapult exploring the potential business case for BESS integration at rail Grid Supply Points in the UK. Stationary storage is a rapidly growing sector in India (with over 5GWh of capacity in the pipeline for the next three years), driven by the steep increase in variable RE power sources and the new Energy Storage Obligation (ESO) on DISCOMs introduced by the Ministry of Power in 2024. Rail GSPs are large capacity demand-only connections which could be attractive system nodes to enlist in the drive to increase network flexibility over coming years, with valuable use cases for renewable load shifting and rail traction client side services (such as improved receptiveness to regenerative braking) as well as providing ancillary services to the grid.