Design and Implementation of Solar PV-Based Railway Microgrid for Linke Hofmann Busch Coaches

Tapesh Yogi[a], Dinesh Birla[a], Dheeraj Kumar Dhaked[b]

[a]Department of Electrical Engineering, Rajasthan Technical University, Kota, India (324010)

[b] Department of Electrical Engineering, Veermata Jijabai Technological Institute

DOI: https://dx.doi.org/10.51244/IJRSI.2025.1210000146

Received: 25 October 2025; Accepted: 30 October 2025; Published: 08 November 2025

ABSTRACT

The demand for reliable, sustainable, and environmentally friendly transportation is the need of the hour, and developments are underway for transportation purposes. The use of DG (diesel generator) sets and fuels increases the emission of carbon dioxide and GHG (greenhouse gases) in transportation. Thus, causing pollution and global warming, which could result in drastic climate change, extinction of living species, rising ocean levels, and natural disasters. Non-conventional power sources like solar power, wind energy, and geothermal energy are emerging as complementary power resources in place of conventional sources. This article has proposed a Solar PV and storage-based system for power solutions of LHB (Linke Hofmann Busch, Germany) coaches used in railway transportation. The integration of this solar PV system within a railway microgrid framework enables intelligent energy management, ensuring efficient coordination between renewable generation, energy storage, and coach power demand. The study has shown that the area available atop train coaches is more than sufficient to generate the required power during sunlight hours. The power will be used through hotel load winding in the locomotive using the HOG (Head on Generation) scheme during cloudy weather and nighttime. Rakes can be used as energy generators while standing in the yard and can feed the energy to the grid, helping to save on tariffs. The total calculation was made by observing a standard running route, the number of coaches, and DG set usage. The cost of diesel is 90.70 INR/liter. In the proposed study, there will be an annual saving of 2,57,75,942 INR, corresponding to 2,84,189 liters of diesel per train per year after implementing this arrangement. The establishment cost of this system would be recovered in approximately five months, as calculated. Hence, the system implemented is a better solution for transportation that is reliable, sustainable, and eco-friendly.

Keywords: LHB Coaches, Railway Micro-Grid, Solar photovoltaic, Transportation, Global horizontal irradiation.

INTRODUCTION

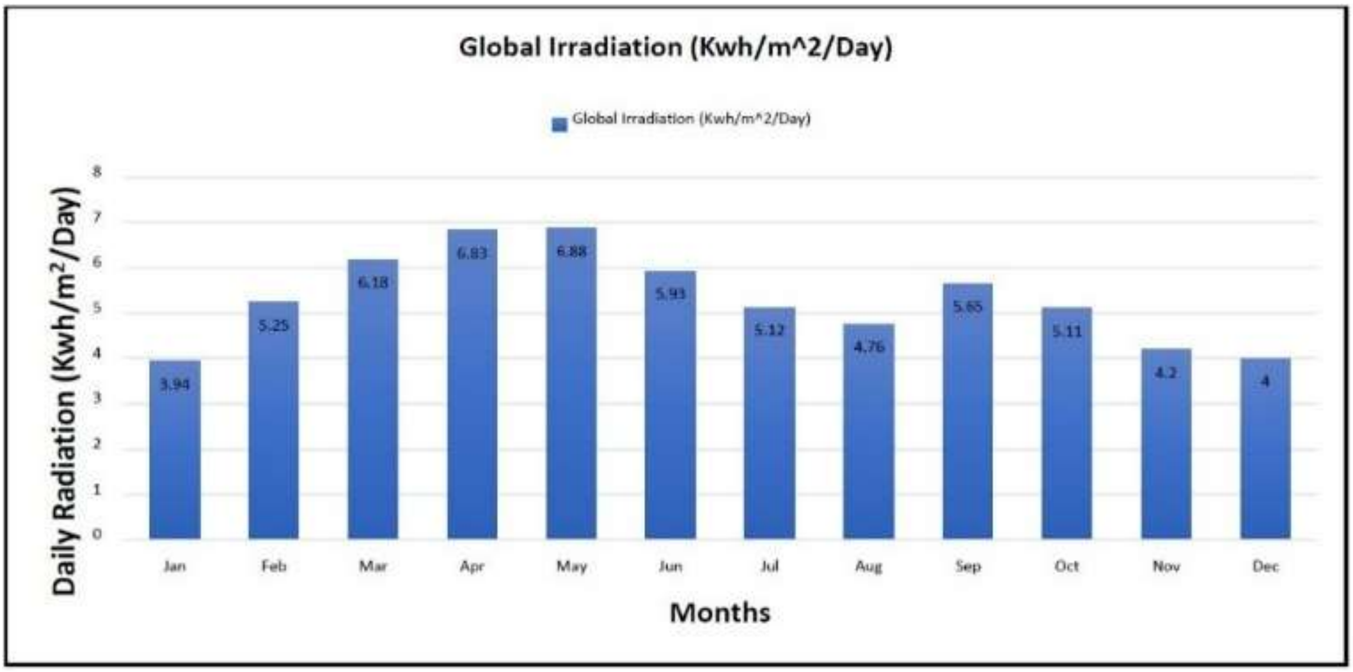
Many energy-consuming sectors are experiencing daily increases in demand and consumption of energy. The transport industry has a peak demand for energy. The International Energy Agency claims that the emissions were produced by the transportation of 8.5 global transport in 2019 but due to the bedtime of covid-19, the good news in 2020 (corona period) is that CO_2 releases from the world transport sector decreased by 10%. The transport sector is a significant contributor to the GHG (Green House Gases) emission of (CO_2) that deteriorates the environment [1]. Numerous fossil fuel sources and some other resources have highly increased global warming due to increased greenhouse gases. Not only it is about the saving of fuel but also a reduction in pollution can take place by using renewable sources for power solutions to the transportation system like Bus, electric bikes, trains, etc. [2-3]. In this paper two coaches of DG sets are replaced with the two passenger coaches. That will help to reduce global warming by supplying power from roof-installed solar panels. A study of the workability of setting up solar photovoltaic (PV) arrays on the rooftop of coaches. This might be big step in depend on conventional energy sources for railway transportation.

A railway microgrid is an integrated energy network designed to manage and optimize the generation, distribution, and consumption of electrical power within railway systems. It combines renewable energy sources such as solar photovoltaic (PV) systems, energy storage units, and intelligent control mechanisms to ensure reliable and sustainable power for traction and non-traction loads. In the context of Linke Hofmann Busch (LHB) coaches, a railway microgrid enables on-board power autonomy through hybrid energy systems, reducing dependency on diesel generators and overhead supply [4]. By incorporating smart energy management, real-time monitoring, and AI-based fault detection and load balancing, railway microgrids enhance operational efficiency, resilience, and environmental sustainability. This approach aligns with Indian Railways' goal of achieving net-zero carbon emissions while improving the reliability and energy efficiency of coach power systems [5].

For the sake of environmental deterioration, Electric powered buses have been introduced by Adelaide city council use power by solar PVs installed on the vehicle's rooftop [6]. Operating costs of renewable energy sources-based buses found less than the conventional energy (diesel/petrol) based [7]. Railways are one of the parts of transportation fields and are popular for their largest transferred capacity, fast running speed, economy, good facility, and superior comfort. Few countries are using the solar photovoltaic system installed on the roof of trains. In Italy, solar panels were installed on five rail coaches of Hamar face leak company [8].

The coaching stock of Indian Railways includes four types of factory coaches [9]. The Linke Hoffman Bosch (LHB) in Germany coaches can run at a much higher speed than ICF coaches and have a 1.7 M long span length than ICF and RCF coaches which accommodate more passengers and provide superior traveling comfort. More areas in LHB coaches over RCF and ICF coaches were found with much more area on the rooftop to mount Solar PV. Hence, old coaches of trains are running across the country, LHB coaches will replace them in next years. So, the focus is on the LHB coaches for this work. Self-generating system (alternators driven by the moving wheels and excels) is not available in LHB coaches but have HOG (Head on generation) system which provides the requisite electrical power in the coach. Various factors such as daylight hours, solar isolation climate conditions like temperature, and humidity in traveling directions, number of halts, speed of the vehicle, quality of the body of the vehicle, and the technology of PV panels installed atop affect the generation of solar power from photovoltaic (PV) panels on a running vehicle (trains, buses, etc.) depends on [10]. The maximum global horizontal irradiation (GHI) of 6.8 kWh/m^2 was recorded in April throughout all of India and the minimum of 3.9 kWh/m^2 in august as depicted in Fig. 1 [11-12].

Fig. 1. Global irradiation [13]



There are 7349 railway stations in India, and around 13169 trains operating on its tracks, with a 12636 km root length network. [14-15]. This shows the amount of energy that can be produced during the LHB coaches of trains staying in Railway yards. The technology would enable significant fuel savings in addition to a decrease in (CO_2) and GHG emissions, which would help to slow global warming [16-17]. The paper [18] examined a

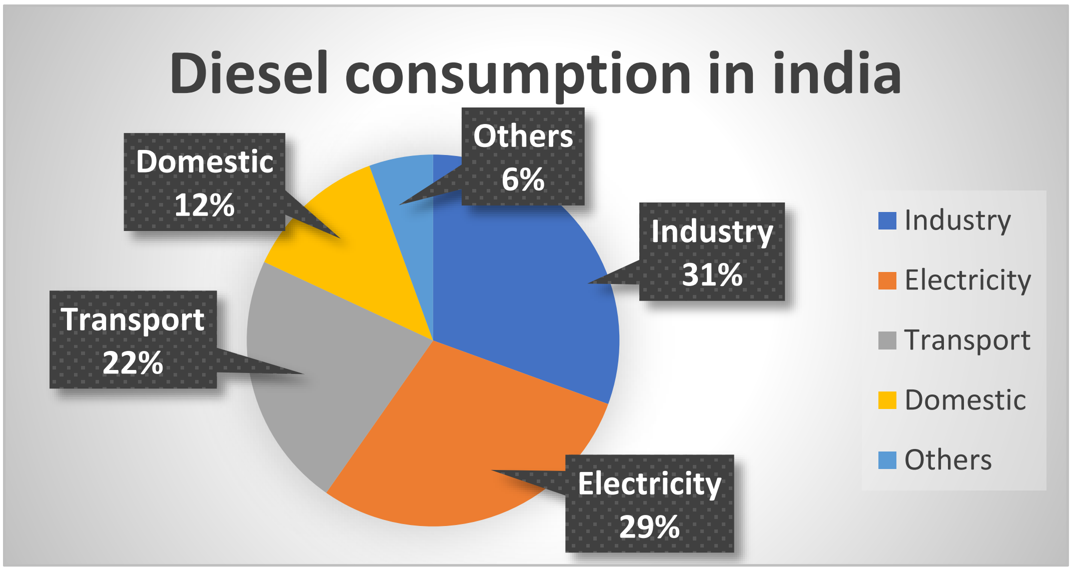
ISSN No. 2321-2705 | DOI: 10.51244/IJRSI | Volume XII Issue X October 2025

folding wings-based solar energy harvesting system (SEHS) technology that produces power for rail applications in railways. Additionally, at load resistance of 5 ohms it has been demonstrated that the prototype generates has max. output power 10.93 W. According to theoretical study and simulation results, the SEHS built next to the Beijing-Tangshan intercity railway generates 673994 kWh of electricity annually. The article has established that solar power can be used to power application on running trains.

A trial solar PV coach on an LHB coach that had been equipped with two flexible 190 wp solar photovoltaic modules was operated by linking to three well-known Indian Railways high-speed trains between Chennai and Mysore, and Chennai and Coimbatore [19]. The project focused on the execution of data collection, monitoring, controlling, and analysis of every system for LHB coaches in Indian railways [20]. This pilot project clears the all concepts about the roof-top solar harvesting system that can help to satisfy the power necessity of the LHB coaches of Indian railways.

The manuscript [21] reports on the viability of complementing fuel-based generator sets with electricity generated by the roof-top solar system. There is a large decrease in (CO_2) emission in addition to fuel conservation. This research has demonstrated that the area available on the roof-top of coaches is more than the required area for generate electricity through solar PVs. The regular route for daily running rail in Indian railways served as the basis for all computations.

Fig. 2. Pie chart of Diesel consumption In India and railways [22]



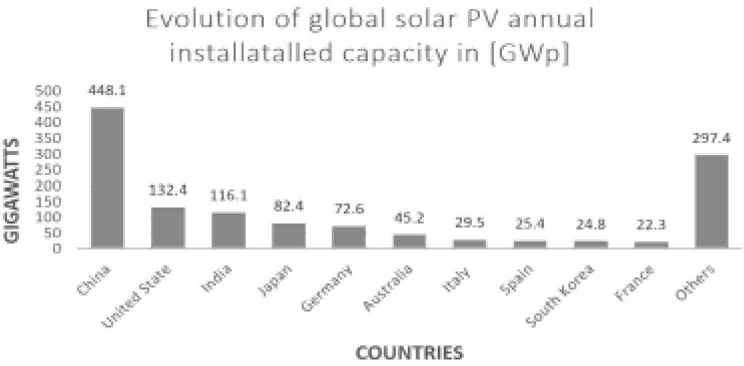
Diesel consumption in Country

- The majority of imported diesel (70 percent) is used in the transportation industry.
- With a share of 22%, the transportation sector has the biggest usage of diesel. Private cars and UVs made up 13.15 percent of this total, followed by commercial cars and UVs at 8.94 percent, three-wheelers at 6.39%, trucks (HCV/LCV) at 28.25 percent, buses at 9.55%, and railroads at 3.24%.
- Another significant consumer, accounting for 13% of overall consumption, is the agricultural sector. The consumption in agriculture is as follows: Pump sets (2.9%), tractors (7.4%), and agricultural equipment (2.7%).
- Other segments consume 17% more diesel than they do. Mobile towers make up 1.54% of this.

The growth of substantial markets of solar power in Asia, as well as in the USA, is showing that the industry is no longer only focused in Europe. Not at all with 147 GW of net fitted capacity, Asif-pacific became the greatest solar energy region in the world by overtaking of Europe history in 2016. Asia-Pacific controlled 70% of the market for new installations in 2018. Germany lost its title as the nation with the most installed capacity to China in 2015. Chinese PV system installations decreased in 2018 from 52.8 GW to 44.4 GW. The nation had an astounding 175 GW of installed capacity as of the end of 2018. Fig. 3 displays the total installed solar PV capacity for various nations.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI | Volume XII Issue X October 2025

Fig. 3. Total PV Cumulative Installed Capacity by Country



India has emerged as a major force on the global PV scene in recent years. India installed 0.6 GW in 2014, a meagre amount. It is expected that India's installed capacity will rise from 27.3 GW in 2018 to116 GW in 2023, or an average annual installation rate of roughly 18 GW [23]. Considerable markets for solar power should expand to emerge in Egypt, Pakistan, Saudi Arabia, Taiwan, Ukraine from now until 2023. These nations currently have a relatively low installed capacity.

The manuscript aims on the uses of renewable energy sources like solar panels used at place of Diesel in railways. So that greenhouse effects, carbon emissions, and pollution can be reduced. This research is organized to first discuss the problem followed by a pollution report due to heavy diesel consumption and carbon emission, and work mentioned in research era. eventually after defining the solution in term of solar PV and HOG system. In first section calculate the solar irradiation, MPPT, and total rooftop area. Consecutive section calculates total solar power generation by panels, and describes the difference between HOG and EOG.

Solar PV unit

A solar PV module can be looked at as a giant solar cell with more voltage & current output compared to one solar cell. Two or more solar cells are connected to designed the solar PV module.

Efficiency of a solar cell determines how much power it can produce. The power produced per unit area is typically in the range of 10 (mW/cm^2) which corresponds to 10% to 25% cell efficiency [24].

A PV unit's power generation is calculated as:

$$P_{pv} = K_{df} \,.\, P_{pv}, \text{rated}. \frac{Ig}{Iem} \quad (1)$$

$$Ppv,rated = \eta pv.Apv.Ipv \quad (2)$$

where,

Kdf = Derating factor

P_{pv}, rated = Rated capacity of PV array

Ig = Actual solar irradiance incident on the solar array (kWh/m^2)

η_{pv} = Conversion efficiency of PV unit

A_{pv} = Area of PV panel (m^2)

I_{pv} = Global solar irradiance

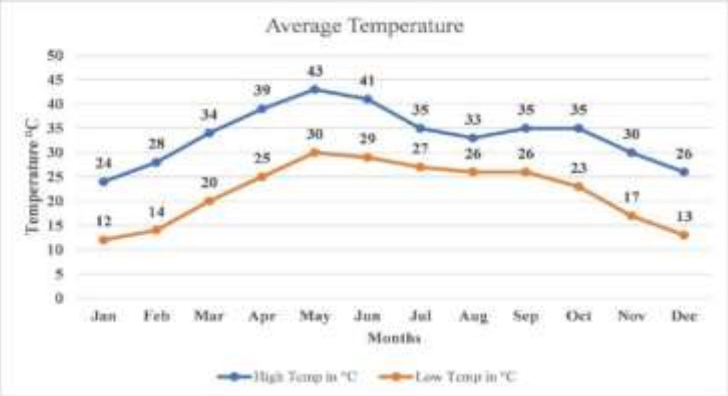
The discrepancy between a PV array's rated performance and its actual performance because of dust, temperature variations, shade, snow cover, ageing, and wire losses is referred to as a derating factor, etc.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI | Volume XII Issue X October 2025

The PV module's efficiency (η_{md}) depends on the properties of PV cell, the modified efficiency of inverter (η_{inv}), the module factor (F_{md}), and the number of connected PV cells (N_{md}). It is given as:

$$\eta_{pv} = \eta_{md}.\eta_{inv}.F_{md}.N_{md} \quad (3)$$

Fig. 4. Average Temperature of the year



The efficiency of PV cells is influenced by reference efficiency (η_{ref}), efficiency coefficient as a function of temperature (β), cell temperature (T_c), and reference cell temperature (T_{ref}).

Hence, PV cell efficiency (η_{cell}) is estimated as

$$\eta_{cell} = \eta_{ref}.\{1 - \beta(T_c - T_{ref})\} \quad (4)$$

Global solar irradiance, ambient temperature (Tamb), and nominal operating temperature (Tnoc) of PV cell affects cell temperature, and is estimated as:

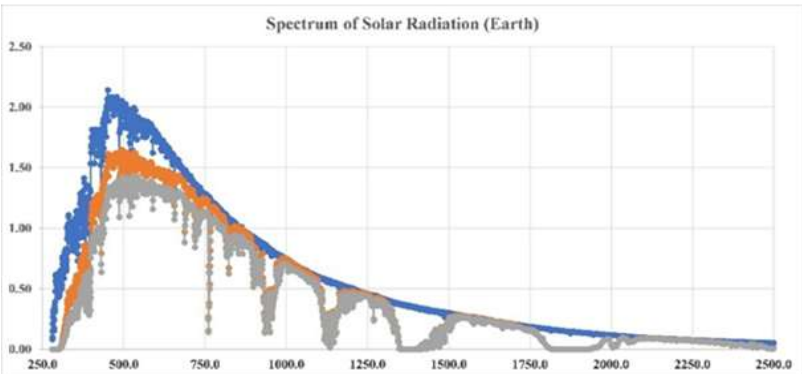
$$T_c = T_{amb}\, I_{pv} \left(\frac{T_{noc} - 20}{800} \right) \quad (5)$$

In Fig. 4 The last year before 2021 saw an average annual temperature of about 27.4o C, up from the year after 1990's average of about 26.9o C. Consequently, it has only marginally risen during the previous 32 years, by roughly 0.6o C. Only the selected 4 Indian weather stations are affected by this trend.

Solar irradiance spectrum

These distributions of energy, give a single common reference as a function of wavelength for the evaluation of spectrally selective PV material in terms of the performance assessed under diver's spectrum distributions of light from various natural and artificial sources.

Fig. 5. Spectrum of Solar Radiation (Earth) [25-28]



A portion of the solar spectrum that solar cells can efficiently absorb and is necessary for solar panels. Wavelength in the solar spectrum span from 100 nm to 1 mm., but most of the irradiance occurs between 250

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI | Volume XII Issue X October 2025

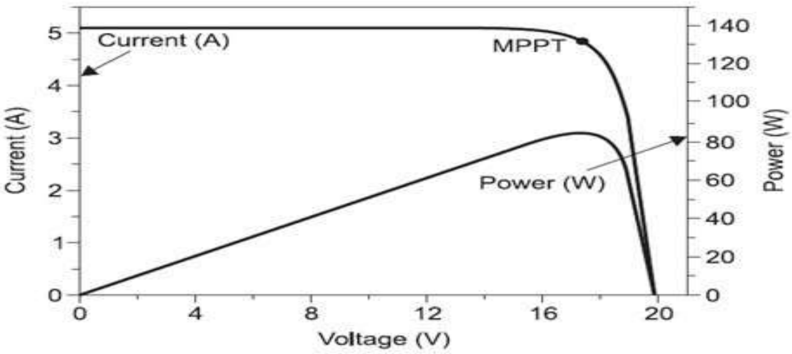
nm and 2500 nm (Fig. 5), with the maximum occurring in the visible region of light (400–700 nm) for air mass (AM) 0, indicating that the cells should attempt to absorb as much of the solar spectrum's visible spectrum as they can.

MPPT (Maximum Power Point Tracking)

The load connected to the module affects the power delivered by PV modules. I-V characteristics of the considered components along with the associated energy outage are displayed in Fig. 6. In a short circuit condition (V=0), The module delivers the largest amount of current is 5.1 Amp. Increasing the load's voltage to 17.3 V, the load is now receiving 84 W more energy. More than this threshold, even when the increasing of voltage, the power output declines because the current is drastically reduced.

Hence, Maximum Power Point refers to the qualities of the power that the module delivers that correlate to its maximum power.

Fig. 6. I-V characteristics and corresponding power are drawn from the Photo Voltaic Module



PV modules must operate at their highest energy point when the photo voltaic cells and load are combined to eliminate the highest power from the modules. The intersection point on the I-V graph of a source to a load is called its operating point.

Details of Train

Concerning daylight hours, the year's longest day is 13 hours 49 minutes while the shortest is 10 hours 10 minutes. The shortest day is 3 hours 38 minutes shorter than the longest one. A median of 2856 hrs of daylight per year (out of a potential 4383), or 7:49 per day [29]. So, it is observed that the train is running to Sunshine for 8 hours during a single trip. This is a good opportunity to utilize the roof-top area to generate energy through solar PV. This is beneficial over, using an EOG (End on generation) system with fossil fuel or diesel. Hence, this study can extract more power from solar instead of diesel generation. The Route of the considered train is shown in Fig. 7, and its load description with fuel consumption details and discussed in Table 1.

Fig. 7. Route Map of the Train Considered in Study

Table 1. Details of the LHB train considered.

Name of the Train	Kota ↔ Nizamuddin (NZM) Jan Shatabdi EXP. (12059-12060)
Rake Composition (22 coaches) No. of A/C coaches No. of Non-A/C coaches No. of EOG No. Extra Parcel coach	3 18 2 1
Distance from source to destination and vice-versa	458+458 = 916 km
Duration of 1 Trip	12 hours 45 min
The total sunshine period during the trip	8 hours
Electrical load Total electrical load per A/c coach Total electrical load of all A/c coaches Total electrical load per Non-A/C coach Total electrical load of Non-A/C coaches Net electrical load of the rake	27 kWh 27 x 3(no. of ac coach) = 81 kWh 4.7 kWh 4.7 x 19(no. of non ac coach) = 89.3 kWh 81 + 89.3 = 170.3 kWh
Details of the fuel used for generator cars Type of fuel used Price per lit of fuel [30]	Hi-Speed Diesel (HSD) INR. 90.70 / lit.
Fuel consumption by generator cars for 1 trip Total capacity of the tank By the net electrical load of the rake	3000 lit. 778.6 lit.
Total cost on fuel for supplying for electrical load during the trip (12 hours 45 min.)	778.6 x 90.70 = 70619 INR

The route map of the train is given in Fig. 7 which is running between the Kota and Nizamuddin stations of Indian railways. More details for the route and train are presented in Table 1.

Rooftop area calculation of LHB Coach for Solar PV Mounting

The typical ICF coaches are 1.7 meters shorter than the LHB coaches., which is useful to mount more solar PV modules on the roof-top. The roof-top layout and calculation of the LHB coach along with the area available for placing the solar PV modules are shown in Fig. 8, 9, and Table 2 respectively.

Fig. 8. Layout LHB Coach.

Fig. 9. Layout of the roof-top of an LHB coach

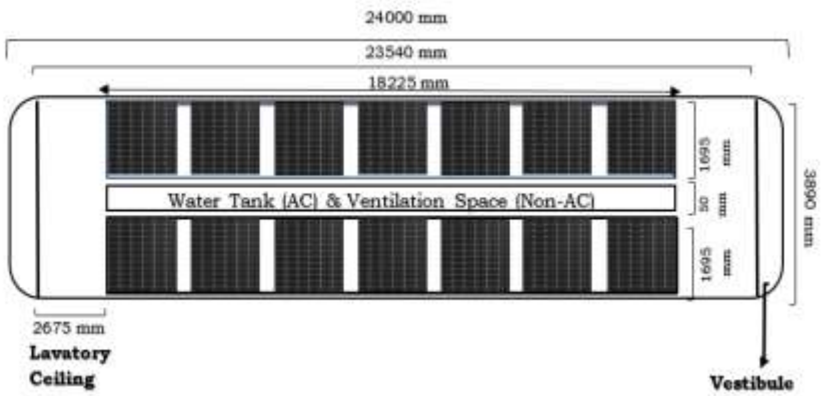


Table 2. Roof-top area available for the mountain of solar PV modules on a single LHB coach.

Net Rooftop area available on an LHB coach	93.36 m2
The area is engaged by Ac units, lavatory ceilings, water tanks, walkways, and ventilation vents.	31.56 m2
Net available area for mounting solar PV modules	61.792

Solar Power Potential per m^2

The panel used for consideration and details are presented in table 3.

Details of Solar (PV) used

Table 3. Features of solar panel considered [31].

Specification	Details
Brand	Loom Solar
Output Power	440-530 W
Required Space	24 ft2
Operating Volatge	24 V
Panel Technology	Mono PERC Bifacial
Additional Features	Cell Conversion Efficiency > 22% (Compliance with IEC standards)
Single Panel Cost of Kw	40,000 INR

Table 4. Power potential of solar PV system on a single LHB coach.

Potential solar energy in a 1 m^2 area	224W
Total potential solar energy in the available space on the roof-top of a single coach	61.79 X 225= 13.84 kW
Net solar power potential observes system efficiency to be 80% and the shaded region as 15%	11.72

Calculation of Solar Power Generation by Solar PV system

It can be observed from Table 3 & 4 that the solar power potential on the roof-top of one LHB coach is averagely higher than the total electrical lighting load of the coach. To check the practicability of the setting up of the solar

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI | Volume XII Issue X October 2025

power system for catering, the average daily GHI is required to be taken into consideration. Fig. 1 describes the tendency of daily GHI averaged over different months of the year. It can be measured that GHI is maximum and minimum during May and January respectively. Table 5 provides the estimate of the energy content that can be generated from solar PV that is installed on the roof of LHB coaches.

Table 5. Total solar power electrical generation by solar PV system.

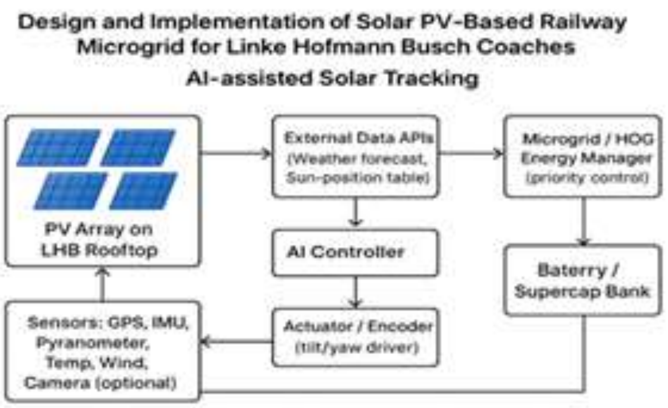
From Table 3, the total area available on the roof-top of the rake (22 coaches considered).	61.79 X 22 = 1359.38 m^2
Net capacity of the solar PV system that can be mounted on the roof-top of the whole rake	11.072 X 22 = 243.58 kW
Total No. of solar PV modules used	609
From Fig. 1, the solar PV system's output when the monthly average daily GHI is	
Maximum (May)	6.8 X 1359 = 9241.2 kWh
Minimum (January)	3.92 X 1359 = 5327.28 kWh
Average daily GHI measured in India (Kota, Rajasthan 2018)	5.32 kwh/m^2
Estimate output of the solar PV system for the average routine GHI measured	5.32 X 1359 = 7229.88 kWh
From Table 1, energy consumed by the net electrical load during sunshine hours (8 hours) of a trip	170 X 8 = 1360 kWh
The volume of diesel drinks up by the electrical load of the rake during the sunshine hours (8 hours) of 1 trip	479.12 lit

As observed by Table 5, the net energy generated by solar is more than the required power. The remaining extra energy will be fed in the overhead lines through Locomotives. It is the same as feeding power at the time of regenerative braking.

AI-Assisted Solar Tracking for Railway Microgrid in LHB Coaches

AI-assisted solar tracking combines short-term irradiance forecasting and a reinforcement-learned controller to continuously orient rooftop PV for maximum yield. Sensors (pyranometer, IMU, temperature, wind, camera) feed a supervised model that predicts irradiance and optimal tilt; an RL/MPC policy then issues safe actuator setpoints balancing energy gain, actuator wear, and wind safety. The tracker coordinates with MPPT and the microgrid/HOG manager to prioritize hotel loads, batteries, or overhead feed-in. Field trials compare fixed, astronomical-tracking, and AI-tracking across varied weather to quantify energy, cost, and CO_2 benefits.

Fig. 10. Block Diagram of AI-assisted Solar Tracking System for Railway Microgrid in LHB Coach.



ISSN No. 2321-2705 | DOI: 10.51244/IJRSI | Volume XII Issue X October 2025

Analysis of HOG energy efficiency when irradiation is not available to generate electricity

The efficiency of the working of the HOG scheme is confirmed by various trials of Indian railways. Electric power required for coaches supplies through the HOG system is used in developing nations. It results in the utilization of SG (self-generation) and EOG systems being limited. It offers excellent operational economic benefits. The savings when using the HOG system as opposed to the EOG system is highlighted in Table 6.

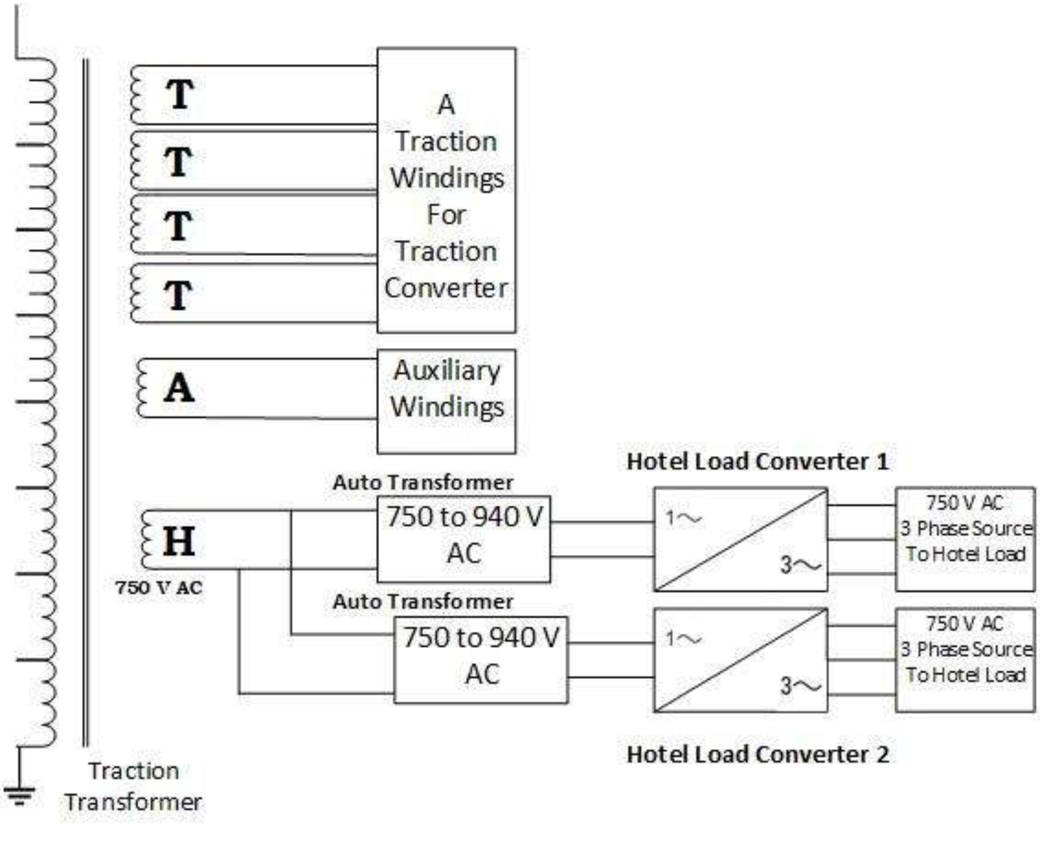
Table 6. Table 6. Saving in expenditure by using HOG over EOG.

Scheme	Energy cost per unit (INR)	Total hotel load	Total run time without solar energy	Total units spend in a trip of 5 Hour	Total energy cost in one trip (INR)	Total annual energy cost
EOG	25	170	5	850	21,250	21,250 X 365 =77.56 lacs INR
HOG	8	170	5	850	6,800	6800 X 365 = 24.82 lacs INR
			Total Saving in year			77.56 – 24.82 = 52.74 lacs INR

HOG System

The train is taking power from the locomotive through hotel load winding during the HOG scheme operation.

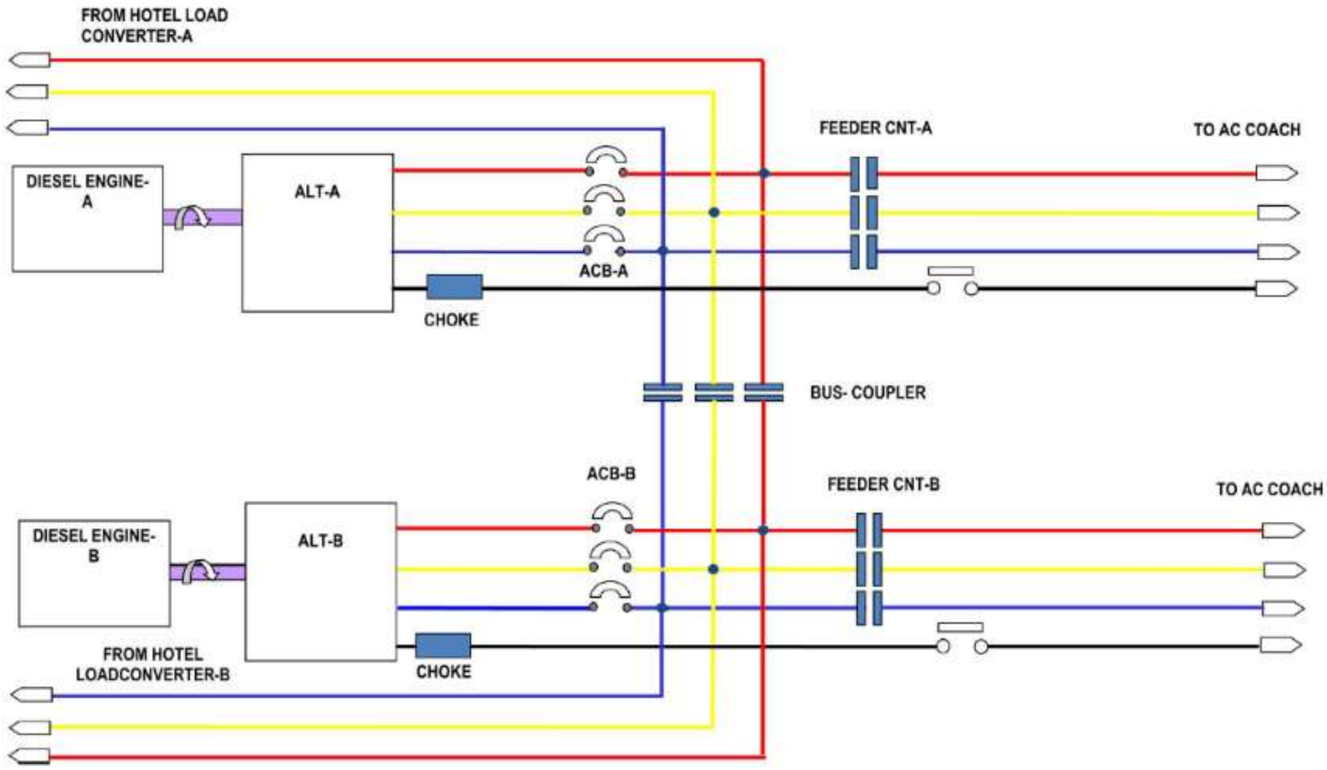
Fig. 11. HOG schematic with single hotel load winding in the loco transformer



The OHE (Overhead lines of 25kv) is used to supply power through the collector (pantograph) to the locomotive's traction transformer, which is installed with a 945 kVA's extra winding, which is known as hotel load winding, at a 1-phase voltage of 750 V, which rise and falls in accordance to the OHE voltage variations shown in Fig. 10.Now this 750 V 1-phase voltage sent to the converter(Hotel load converter), as shown in Fig. 11, which provides 750 V, 3-phase, 50 Hz power supply as an output for the train's hotel load.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI | Volume XII Issue X October 2025

Fig. 12. EOG Block Diagram with HOG Supply [32]



Expenditure saving for considered rail route

A total expenditure of 52.74 lacs INR can be recovered yearly by the regular operation of the HOG system whenever Solar PV does not generate electricity. However, the train plying 8 hours in sunshine period and only 4 hours 45 min without getting solar energy but considered around 5 hours by considering the situation of being late to reach the destination or considering cloudy weather.

Annual reduction in CO_2

The train considered is assumed to make up to 365 trips in the year because it runs daily. The arrangement can get the benefits mentioned in the next Table 7 along with a large reduction in (CO_2) emissions. The carbon composition of the fuel determines how much (CO_2) is created after it has burned. When a fuel is burned, its carbon (C) and hydrogen (H) contents primarily govern how much energy is released. When oxygen (O) and carbon (C) mix during combustion, heat is created. Diesel weighs 835 grams per liter and contains 86.2% carbon. This carbon requires 1920 grams of oxygen to burn, producing (CO_2). 720+1920 = 2640 grams (2.64kg) of carbon-ignited diesel is the result.[33]

Table 7. Annual reduction in CO2.

The maximum number of trips in a year	365
The volume of diesel that can be annually consumed by the EOG system of train	365 X 778.6 = 2,84,189 lit.
Annual reduction in the CO_2 emitted by a train, taking the amount of CO_2 emitted per liter of diesel burnt as 2.64 kg and factor of combustion as 0.99	2,84,189 X 2.64 = 755942.74 kg (756 tons)

Impact of this scheme

The train considered requires 170 kWh power but considering some variation time so 200 kW PV system will be installed on the rooftop of a train rake. The cost per kW solar PV installation is around 40,000 INR/kW. The total cost of mounting solar PV will be returned in 5 months by this scheme.

Table 8. Savings and Return of Investment (ROI) of the considered system.

The total cost of mounting Solar PV on the Roof-top of a train	40,000 X 200 = 80,00,000 INR
Total annual cost on diesel in EOG scheme	2,84,189 X 90.70 = 2,57,75,942 INR
Saving of diesel Daily saving by using Solar power Daily saving by using the HOG scheme Total savings from both per day	34,496 INR 21,560 INR 56,056 INR
Return on investment (ROI)	80lacks INR/56,056 = 143 days (Around 5 Months)

Hardware Setup

The hardware setup implements of converter and WaveCT WCU300 with the MATLAB Simulink installed system. The WaveCT WCU300 is a versatile solar charge controller designed to efficiently manage the power flow from solar panels to batteries. It is a suitable choice for various applications, including rooftop solar systems on Indian Railways coaches.

Fig. 13. Hardware Setup

The WaveCT WCU300 is a promising solar charge controller for Indian Railways coaches, offering efficient power management and various protection features. By implementing solar power systems on coaches, Indian Railways can contribute to a more sustainable and environmentally friendly transportation sector.

CONCLUSION

This article is fundamentally accessing the solar PV uses in the transportation system of railways:

- Net available area for mounting solar PV modules on a single LHB coach is 61.79 (m^2) hence total available area on the rooftop of the whole rake is 1359 (m^2) (considered 22 coaches). According to the above calculation in Table 5, 609 solar PV modules are used to generate 243.2 kW power for the whole rake.
- It has been calculated that the volume of diesel conserved per year per train is around 2,84,189 lit. causing a reduction of 755 tons of (CO_2) being emitted into the atmosphere.
- The total cost of installing solar PV on the rooftop of the train is 80,00,000 INR. By using this arrangement 56056 INR of diesel got saved.
- The ROI of the system installed is 143 days i.e., 4 months 23 days.

- The benefit of this research by observing calculation and measurement is saving money, reducing (CO_2) emissions, reducing global warming, and can replacement of 2 EOG coaches with passenger coaches. So, the capacity of transportation is also increased.

REFERENCES

1. International Energy Agency. Report, "Global CO2 emissions from transport by subsector," https://www.iea.org/data-and-statistics/charts/global-CO2-emissions-from-transport-by-subsector-2000-2030, (2021).
2. Doulgeris, S., et al. "Evaluation of energy consumption and electric range of battery electric busses for application to public transportation." Transportation Engineering 15 : 100223 (2024).
3. Hao D, Zhang T, Guo L, Feng Y, Zhang Z, Yuan Y. A High-Efficiency, Portable Solar Energy-Harvesting System Based on a Foldable-Wings Mechanism for Self-Powered Applications in Railways. Energy Technology. (4) :2000794 (2021).
4. Cabrane, Zineb, and Soo Hyoung Lee. "Control and management of railway system connected to microgrid stations." IEEE Access 10 (2022): 40445-40455.
5. Jafari Kaleybar, Hamed, et al. "Smart AC-DC Coupled Hybrid Railway Microgrids Integrated with Renewable Energy Sources: Current and Next Generation Architectures." Energies 17.5 (2024): 1179.
6. Dhaked DK, Gopal Y, Birla D. Battery charging optimization of solar energy-based telecom sites in India. Engineering, Technology & Applied Science Research ;9(6):5041-6. (2019).
7. Dhaked DK, Gopal Y, Birla D. Battery charging optimization of solar energy based telecom sites in India. Engineering, Technology & Applied Science Research.;9(6):5041-6, (2019).
8. Di Pasquale, Antonio, et al. "Optimal Sizing of a Wayside PV System for DC Rail Transit Systems: The Case Study of the 3 kV Cagliari-Oristano Traction System." 2024 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC). IEEE, (2024).
9. Indian. Railways, "INDIAN RAILWAYS Lifeline to the Nation, "Indian Railways. [Online]. Available: https://indianrailways.gov.in/railwayboard/view_section.jsp?lang=0&id=0,1,304,366,552,694, (2021).
10. Akhtar I, Kirmani S, Hasan S. Advanced control approach for solar assisted electric vehicle drive. Materials Today: Proceedings. 1;46:10806-10, (2021).
11. Iskandar, Handoko Rusiana, et al. "The Green Campus Building's Rooftop Photovoltaic System Design Project." Infotekmesin 15.1: 24-32, (2024).
12. Indian solar resources map, "Global Solar Atlas," Ministry of New and Renewable Energy. [Online]. Available: https://globalsolaratlas.info/download/india, 13 Oct (2019).
13. Elkasrawy, Mohamed A., et al. "Harnessing Solar Energy for Charity: Implementation and Monitoring of a 5 kWp Photovoltaic System." 2024 25th International Middle East Power System Conference (MEPCON). IEEE, (2024).
14. Indian Railways, "INDIAN RAILWAYS Lifeline to the Nation," INDIAN RAILWAYS, 03 July 2019. [Online]. Available: https://indianrailways.gov.in/railwayboard/view_section.jsp?lang=0&id=0,1. [Accessed 23 Oct 2022].
15. Sipra, Abdullah Tariq, et al. "Design and assessment of energy management strategy on rail coaches using solar PV and battery storage to reduce diesel fuel consumption." Energy 288: 129718, (2024).
16. Hao D, Zhang T, Guo L, Feng Y, Zhang Z, Yuan Y. A High-Efficiency, Portable Solar Energy-Harvesting System Based on a Foldable-Wings Mechanism for Self-Powered Applications in Railways. Energy Technology. (4):2000794, (2021).
17. Darvishpour, Yasaman, et al. "Integration of Rooftop Solar PV on Trains: Comparative Analysis of MPPT Methods for Auxiliary Power Supply of Locomotives in Milan." Electronics 13.17: 3537, (2024).
18. Hao D, Zhang T, Guo L, Feng Y, Zhang Z, Yuan Y. A High-Efficiency, Portable Solar Energy-Harvesting System Based on a Foldable-Wings Mechanism for Self-Powered Applications in Railways. Energy Technology. (4):2000794, (2022).
19. Anh, An Thi Hoai Thu, and Tran Hung Cuong. "A Solution for Energy-Efficient Operation of Urban Electric Trains: Integrating Rooftop PV with the Active Rectifier in the Traction Substation." Engineering, Technology & Applied Science Research : 13890-13896, (2024).
20. Dunlap, Richard A. Transportation Technologies for a Sustainable Future: Renewable energy options

for road, rail, marine and air transportation. IOP Publishing, (2023).
21. Bagal, Dilip Kumar, et al. "Scope of Using Photovoltaic Cell to Power Electrical Units of Air-Conditioned Linke Hofmann Busch (LHB) Coaches Used in Indian Railways." Advances in Air Conditioning and Refrigeration: Select Proceedings of RAAR 2019. Springer Singapore,(2021).
22. Smartkeeda, “smartkeeda,” [Online]. Available: https://www.smartkeeda.com/Myfiles/images/1(8).png, 10 Sep 2021.
23. Dhaked DK, Birla D. Microgrid designing for electrical two-wheeler charging station supported by solar PV and fuel cell. Indian Journal of Science and Technology.14(30):2517-25, (2021).
24. Dhaked DK, Birla D. Modeling and control of a solar-thermal dish-stirling coupled PMDC generator and battery based DC microgrid in the framework of the ENERGY NEXUS. Energy Nexus. 16;5:100048, (2022).
25. Fakiola, Christina. Radiative transfer in dust shells around red giant stars. MS thesis. ETH Zurich, 2023.
26. Abreu, Edgar Francisco Mendes. Direct Normal Irradiance and circumsolar radiation: modelling, measurement and impact on Concentrating Solar Power. Diss. Universidade de Evora (Portugal), (2023).
27. Driesse, Anton, Marios Theristis, and Joshua S. Stein. Global horizontal spectral irradiance and module spectral response measurements: an open dataset for PV research. No. SAND-2023-02045. Sandia National Lab.(SNL-CA), Livermore, CA (United States); Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), (2023).
28. Xue, Yanqun, and Sanekazu Igari. "Reference solar spectra and their generation models." Journal of Science and Technology in Lighting 46: 6-18, (2023).
29. Govt. Of India, “Sunshine and daylight hours in New Delhi, India,” Sunshine and daylight hours in New Delhi, India . [Online]. Available: https://www.new-delhi.climatemps.com/sunlight.php, (2022).
30. N. Valev, “GlobalPetrolPrices.com,” GlobalPetrolPrices. [Online]. Available: https://www.globalpetrolprices.com/USA/diesel_prices/, (2022).
31. L. Solar, “Loom Solar,” Shark Bi-Facial Solar Panel 440-530 Watt. 144 Cells, 9 Bus-Bar. [Online]. Available: https://www.loomsolar.com/products/shark-bifacial-front-back-power-generation-solar-panel (2022).
32. Sharma, Sanjeev, et al. "A comprehensive review of Indian railway freight business: Strategies for regaining the lost ground and future prospects." Case Studies on Transport Policy: 101195, (2024).
33. Ecoscore, “Ecoscore,” [Online]. Available: https://ecoscore.be/en/info/ecoscore/CO2, (2022).

AI-Assisted Solar Tracking For Lhb Coach Microgrids

AI-assisted solar tracking combines short-term irradiance forecasting and a reinforcement-learned controller to continuously orient rooftop PV for maximum yield. Sensors (pyranometer, IMU, temperature, wind, camera) feed a supervised model that predicts irradiance and optimal tilt; an RL/MPC policy then issues safe actuator setpoints balancing energy gain, actuator wear, and wind safety. The tracker coordinates with MPPT and the microgrid/HOG manager to prioritize hotel loads, batteries, or overhead feed-in. Field trials compare fixed, astronomical-tracking, and AI-tracking across varied weather to quantify energy, cost, and CO_2 benefits.

Figure: Block Diagram of AI-assisted Solar Tracking System for Railway Microgrid in LHB Coach.