International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Life Cycle Assessment and Environmental Impact Analysis of a 40kW Rooftop Solar Power System in Madhya Pradesh

Prahlad Harinakhede[1], Dr. Ruchi Pandey[2]

[1] PG Scholar Electrical Department GGITS
[2] Electrical Department GGITS

ABSTRACT:

This research presents a Life Cycle Assessment (LCA) of a 40kW rooftop solar system installed in Majholi, Madhya Pradesh, comprising Adani bifacial panels, a Havells on-grid inverter, and a GI mounting structure. It evaluates environmental impacts across all life cycle stages—material extraction, manufacturing, transport, installation, operation, and disposal. Key findings include an energy payback time of approximately 2.5 years and a reduction of 60–80 metric tons of CO_2 over its lifetime. High recyclability of materials like aluminum, glass, and steel enhances sustainability. The study underscores the long-term environmental benefits of rooftop solar systems and suggests future improvements in panel efficiency, inverter tech, and smart grid integration to boost performance and scalability.

Keywords: Life Cycle Assessment (LCA), Rooftop Solar System, Environmental Impact

Introduction

In this research work, case study of Mahila Shakti Sangh Solar power requirement, installation and life cycle assessment has been. This chapter starts with the company profile, Current power consumption, Solar panel design consideration, installment and Life cycle assessment *Mahila Shakti Sangh* is a grassroots organization based in *Majholi [10]*, dedicated to empowering women through various social, economic, and community initiatives. Established with the vision of enhancing the socio-economic standing of rural women, the Sangh actively works to promote self-reliance, financial independence, and skill development among women in the region. The office building at which solar plant is installed is shown below

Installed Solar plant details

40kW solar plant system components are mentioned in the figure below

S.NO.	Equipment and Description	Make
1.	Bifacial Panels (upto 10-20% more efficient panels than Mono Panels) Module 540watt*74 nos.	Adani
2.	Ongrid Solar Inverter 40 KW three phase	Havells
3.	Solar DC Cable, 4 sq mm. / 6 sq. mm.	RR Kabel/Polycab
4.	ACDB, DCDB	Havells
5.	AC Cable, 16/25 sq. mm	Reputed Make
6.	Module Mounting Structure 3*5 Height	Galvanized C Chanel with Nut &Bolds(SS)
7.	MC4 Connector	Reputed Make
8.	Earthing	Copper Electrode Earthing 3 Nos.
9.	Lightening Arrestor	Copper 2 Nos.
10.	Smart meter	Avon (govt. approved)

Figure 1 Details of components used in 40kW solar plant

Solar panel

In the discussed premises, bifacial solar panel has been used. Bifacial solar panels are an advanced photovoltaic technology designed to capture sunlight on both sides of the panel, maximizing energy generation. Unlike traditional monofacial panels, which only absorb light on their front surface, bifacial panels have transparent backsheets or dual glass structures that allow sunlight reflected from the ground or nearby surfaces to hit the rear side. This results in increased efficiency, particularly in environments with high ground albedo (reflectivity), such as snowy, sandy, or concrete-covered areas. Solar panel name plate is shown in the figure below

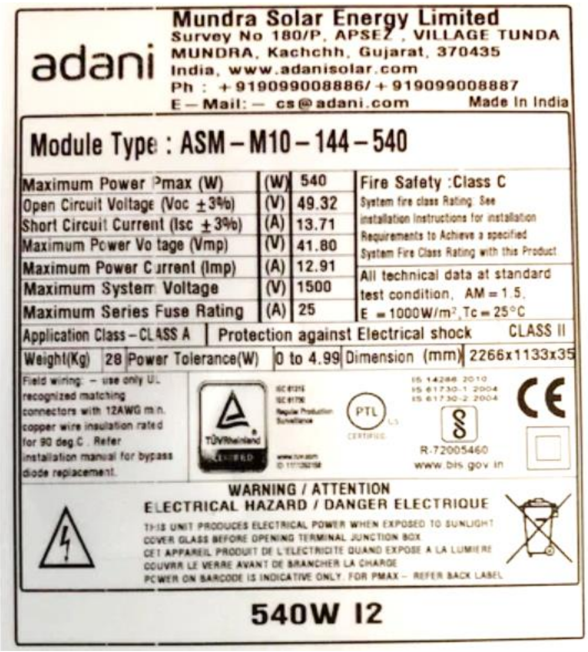

Figure 2 Solar panel name plate

The panels can be installed at different angles, either tilted or vertically, to optimize sunlight exposure from both direct sunlight and reflected light. By harnessing the additional energy from the rear side, bifacial panels can generate up to 30% more electricity compared to monofacial counterparts, depending on environmental conditions and installation setups.

Due to their durable design, often using glass on both sides, bifacial panels also have a longer lifespan and better resilience to environmental stressors. However, they are generally more expensive than traditional panels, and their performance heavily depends on the installation environment. Despite the higher initial cost, the enhanced energy yield and durability make bifacial panels a promising solution for large-scale solar projects and high-efficiency installations.

Total **74** panels has been used. Power rating of each solar panel is **540W**. Maximum capacity from the solar panel is 74 * 540 = **40kW (approx.)**

Life Cycle Assessment (LCA) of 74 Solar Panels (Adani Solar, 540W Each)

The life cycle assessment (LCA) of solar panels provides a comprehensive evaluation of the environmental impacts associated with each phase of the product's life, from raw material extraction to manufacturing, transportation, operation, and end-of-life disposal or recycling. In this case, we will assess the LCA of 74 Adani Solar panels, each with a capacity of 540W, amounting to a total capacity of 39.96 kW.

Raw Material Extraction and Manufacturing

Adani Solar panels are primarily made from silicon, glass, aluminum, and polymers. The key stages in manufacturing include silicon extraction, wafer production, cell assembly, and panel construction. The energy-intensive silicon purification and wafer production processes are significant contributors to the overall environmental impact.

Table 1 Material consumption in solar panel manufacturing

Material	*Function*	*Quantity per Panel*	*Total for 74 Panels*
Silicon	Photovoltaic cell material	3 kg	222 kg
Glass	Encapsulation and protection	15 kg	1110 kg
Aluminum	Frame and structural support	5 kg	370 kg
Polymers (EVA, etc.)	Insulation and lamination	1.2 kg	88.8 kg

The manufacturing process of one 540W panel emits around *450-500 kg CO_2 equivalent* due to the energy required for raw material extraction, processing, and assembly.

Transportation

Transportation of solar panels from the manufacturing facility to the installation site involves the use of trucks or ships, depending on the distance. Assuming these panels are transported over 1,500 kilometers from Adani's manufacturing plant in India to the installation site, the emissions associated with transportation are calculated based on fuel consumption and vehicle efficiency.

- *Total weight per panel*: Approximately 25 kg
- *Total weight for 74 panels*: 1850 kg
- *Emission factor for road transport*: 0.1 kg CO_2 per ton-km

Thus, for 74 panels over 1,500 km, the transportation emissions are:

$$Emissions = 1.85\ tons * 1500\ km * 0.1kg\frac{CO_2}{ton-km} = 277.5kg\ CO_{2^2}$$

Installation

During the installation phase, the panels are mounted on supporting structures, typically made of steel or aluminum. The impact from installation is minimal compared to other phases, but it involves the use of machinery (cranes, etc.), manual labor, and energy.

- *Total installation emissions*: Estimated at *10-15 kg CO_2* per panel.

Operational Phase (Energy Generation)

The panels are designed to generate electricity for 25-30 years with minimal degradation. Each panel, with a capacity of 540W, operates at around 80-85% efficiency over its lifespan. Assuming an average capacity factor of *20%* (accounting for weather, orientation, and site conditions), each panel produces approximately *950 kWh per year*.

For 74 panels:

$$Annual\ energy\ generation\ = 950kWh * 74 = \mathbf{70,300\frac{kWh}{Year}}$$

Over 25 years, the total energy generated will be:

$$Total\ energy\ generation = 70{,}300\frac{kWh}{Year} * 25 = \mathbf{1,757,500\ kWh}$$

End of Life (Recycling and Disposal)

After 25-30 years, solar panels typically reach the end of their useful life. The disposal or recycling of the panels involves disassembly and recovery of valuable materials like silicon, glass, and metals. Recycling reduces the need for virgin material extraction, thus lowering the overall environmental impact.
Recycling potential: 85-90% of the panel's materials are recyclable, particularly aluminum frames, glass, and silicon.
End-of-life emissions: Minimal, as recycling processes offset much of the environmental cost.

Environmental Impact Summary

Table 2 Environmental impact summary from solar panel

Life Cycle Stage	*Estimated Emissions (kg CO_2/panel)*	*Total Emissions for 74 Panels (kg CO_2)*
Raw Material & Manufacturing	500	37,000
Transportation	4	277.5
Installation	15	1,110
Operation (Emission Savings)	Negative (Energy generation offsets)	Energy savings over lifespan
End of Life	Minimal (due to recycling)	Minimal

The LCA of 74 Adani Solar panels, each with a capacity of 540W, reveals that while the initial environmental impact from manufacturing and transportation is significant (about *38,387.5 kg* CO_2), the panels' operational phase offers substantial emissions savings by generating clean energy. Over their 25-year lifespan, these panels will produce approximately *1.76 GWh* of electricity, effectively offsetting a considerable amount of carbon emissions. Moreover, with 85-90% recyclability, the end-of-life phase has a minimal environmental footprint. Thus, solar panels provide a net positive environmental impact by displacing fossil fuel-based energy generation, contributing to global decarbonization efforts.

Ongrid Solar inverter

In the premises, Havell's solar on grid inverter of 40kW is used. A solar on-grid inverter, also known as a grid-tied or grid-connected inverter, is a critical component of modern solar power systems that are directly connected to the electrical grid. Its primary function is to convert the direct current (DC) generated by photovoltaic (PV) solar panels into alternating current (AC), which is the form of electricity compatible with both household appliances and the utility grid. Unlike off-grid inverters that rely on batteries for storage and operation, on-grid inverters do not require batteries. They work in harmony with the grid, using it as a backup power source when solar energy production is low or when demand exceeds generation. This type of system is particularly popular in urban and suburban areas because of its efficiency, ease of use, and potential for economic benefits through programs like net metering.

Figure 3 Havell 40kW solar on grid inverter

The advantages of solar on-grid inverters are numerous. One of the primary benefits is their cost-efficiency, as they eliminate the need for expensive batteries by using the grid as a virtual storage system. This not only reduces upfront costs but also simplifies installation and maintenance. Moreover, on-grid inverters enhance energy efficiency since there are no storage-related energy losses. They ensure that the maximum amount of solar energy is either used or fed into the grid. Through net metering, users can earn credits for the excess energy they produce, making solar on-grid systems financially attractive in many regions. Additionally, the simplicity of on-grid systems makes them ideal for urban environments where space may be limited, as there is no need for large battery banksIn conclusion, solar on-grid inverters are essential for connecting solar energy systems to the electrical grid, making them an accessible and economical solution for those seeking to harness solar power. By efficiently converting DC to AC and providing seamless grid integration, they enable solar power to be used in real-time while offering financial incentives through surplus energy sales. This technology continues to drive the adoption of solar energy in residential and commercial applications worldwide.

Life cycle assessment of 40kW solar on grid inverter

To present the Life Cycle Assessment (LCA) of a 40kW Havells solar on-grid inverter clearly and concisely, the following table breaks down each stage of the inverter's life cycle, identifying its key environmental impacts, benefits, and areas for potential improvement.

Table 3 Life Cycle Assessment (LCA) of a 40kW Havells solar on-grid inverter

Life Cycle Stage	*Key Processes*	*Environmental Impact*	*Potential Improvements*
1. Raw Material Extraction & Manufacturing	- Extraction of metals (copper, aluminum, silicon) - Processing and component manufacturing	- Resource depletion - Energy consumption - Emissions from material processing	- Use recycled materials - Improve energy efficiency in manufacturing
2. Transportation & Installation	- Transport from factory to site - Installation on-site	- Emissions from transportation - Minor impact from installation equipment	- Optimize logistics - Use eco-friendly transport methods
3. Operational Stage	- Conversion of DC to AC - Grid synchronization	- High efficiency minimizes energy loss - Low standby power	- Increase conversion efficiency to reduce losses further

Life Cycle Stage	*Key Processes*	*Environmental Impact*	*Potential Improvements*
		consumption	
4. Maintenance	- Periodic checks - Component replacements (capacitors, etc.)	- Energy and resources used in maintenance - Component degradation	- Extend component life through design improvements - Use long-lasting parts
5. End-of-Life & Recycling	- Disposal or recycling of electronic components	- Potential e-waste if improperly disposed - Recycling saves valuable materials	- Develop take-back programs for recycling - Design for easier disassembly

Detailed Analysis:

Raw Material Extraction & Manufacturing

The first stage of the LCA involves extracting raw materials, including metals like copper, aluminum, and silicon. These are crucial for the inverter's circuitry and housing. The manufacturing process also consumes energy and resources, generating greenhouse gas emissions.

Table 4 Material used for inverter (non electronic)

Material Used	*Purpose*	*Environmental Impact*
Copper	Wiring and circuits	Resource depletion, mining-related emissions
Aluminum	Casing and heat sinks	Energy-intensive extraction, emissions
Silicon	Semiconductors	Energy for purification and processing

Potential Improvements: Sourcing recycled metals or optimizing energy efficiency in production can lower the environmental footprint.

Transportation & Installation

Once manufactured, the inverter is transported to the installation site. Transportation contributes to carbon emissions, depending on the distance and means of transport. Installation has a relatively low environmental impact but requires minimal materials and manpower.

Table 5 Inverter transportation

Transport Mode	*Impact*	*Installation Requirements*
Truck or Sea Freight	Emissions based on fuel consumption	Electrical connection and mounting
Installation Equipment	Minor impact from tool use	Low material consumption

Potential Improvements: Optimizing logistics, such as shipping efficiency or using low-emission transport, could reduce the transportation impact.

Operational Stage

During operation, the 40kW Havells inverter converts DC electricity from solar panels to grid-compatible AC, enabling solar energy to power homes and businesses. This stage is the most environmentally beneficial, as it enables renewable energy use.

Table 6 Operational analysis of solar inverter

Performance Metric	*Value*	*Impact*
Conversion Efficiency	> 95%	Minimal energy loss, low emissions
Standby Power Consumption	Very low (few watts)	Continuous but minor energy usage

Potential Improvements: Increasing the inverter's conversion efficiency even further could further reduce energy losses.

Maintenance

Maintenance involves occasional replacement of parts, such as capacitors, which degrade over time. The environmental impact of this stage is minimal but involves resource consumption for part replacements.

Table 7 Maintenance analysis of solar inverter

Component	*Replacement Frequency*	*Environmental Impact*
Capacitors	Every 7-10 years	Minor material and energy usage for replacements

Potential Improvements: Designing longer-lasting components could extend maintenance intervals and reduce the environmental impact over time.

End-of-Life & Recycling

At the end of its life cycle, the inverter must be either recycled or disposed of. Recycling reduces e-waste and recovers valuable materials, but improper disposal can result in environmental harm due to toxic components.

Table 8 End of life cycle for solar inverter

Material	*Recyclability*	*Impact if Not Recycled*
Metals (copper, aluminum)	High	Resource wastage and e-waste pollution

Material	*Recyclability*	*Impact if Not Recycled*
Electronic Components	Moderate to High	Potential for harmful e-waste

Potential Improvements: Developing recycling programs or designing for easy disassembly could improve the sustainability of the end-of-life stage.

The Life Cycle Assessment of a 40kW Havells solar on-grid inverter highlights that while there are environmental impacts during material extraction, manufacturing, and maintenance, the operational stage offers significant environmental benefits by enabling the use of clean solar energy. Improvements in recycling practices, energy efficiency, and material sourcing can further reduce the overall footprint, making this inverter a more sustainable choice for solar energy systems.

GI roof top structure

A Life Cycle Assessment (LCA) of a galvanized iron (GI) rooftop structure for a 40kW solar panel system evaluates the environmental impacts throughout its entire life cycle, from material extraction to disposal. The rooftop structure plays a crucial role in supporting and securing solar panels, ensuring optimal orientation and durability. Conducting an LCA helps assess the sustainability of the GI structure and identifies areas where improvements can be made to reduce its environmental footprint.

Figure4 GI roof top structure

Raw Material Extraction and Manufacturing

The primary material used in rooftop structures for solar panels is galvanized iron (GI), a form of steel that is coated with a protective layer of zinc to prevent corrosion. The life cycle begins with the extraction of iron ore and zinc, both of which are energy-intensive processes. These raw materials undergo smelting and processing to produce steel, which is then galvanized through a process involving molten zinc.

Table 9 Raw Material Extraction and Manufacturing for GI support structure

Material	*Purpose*	*Environmental Impact*
Iron	Base material for structural strength	Energy use, mining impacts, greenhouse gas (GHG) emissions
Zinc	Corrosion protection (galvanization)	Resource depletion, high energy consumption in extraction

The manufacturing stage involves shaping, cutting, and welding the GI material into components like rails, brackets, and mounting structures. This phase also consumes significant energy and generates emissions from industrial processes. However, the durability of GI helps extend the lifespan of the structure, reducing the need for frequent replacements.

Potential Improvements: Reducing the energy consumption in manufacturing and exploring the use of recycled steel and zinc can lower the environmental impact. Additionally, enhancing manufacturing efficiency and minimizing material waste during production can also contribute to a reduced footprint.

Transportation and Installation

Once manufactured, the GI rooftop structure components are transported to the installation site. This stage typically involves emissions from the use of fossil-fuel-powered vehicles, depending on the distance from the factory to the installation location.

Table 10 Transportation and installation analysis of GI structure

Stage	*Environmental Impact*
Transportation	Fuel consumption, GHG emissions during transit
Installation Process	Minimal environmental impact from assembly tools

The installation process itself involves assembling the GI structure on the rooftop, which usually has a minor environmental impact as it requires only basic tools and labor. However, proper installation ensures the long-term durability and stability of the structure, supporting the 40kW solar panel system for decades.

Potential Improvements: Optimizing the logistics and transportation routes, as well as using fuel-efficient or electric vehicles, can reduce the carbon footprint of the transportation stage.

Operational Stage

During the operational stage, the GI structure provides a stable and durable foundation for the solar panels, allowing them to capture sunlight and generate electricity. The environmental impact at this stage is minimal, as the structure does not emit any pollutants or consume resources during operation. However, its ability to withstand harsh weather conditions and prevent corrosion is key to ensuring the long-term functionality of the solar panel system.

Table 11 Durability and lifetime analysis of GI structure

Performance Metric	*Value*
Durability	High resistance to corrosion and weather
Lifespan	25-30 years (aligned with the lifespan of solar panels)

Potential Improvements: Although the environmental impact during operation is minimal, further research into more corrosion-resistant materials or coatings that require less zinc could make the structure even more sustainable.

Maintenance

The GI rooftop structure typically requires little to no maintenance during its operational life due to its corrosion-resistant properties. However, periodic inspections may be necessary to ensure structural integrity, especially in regions prone to extreme weather. Minor repairs, such as tightening bolts or replacing damaged parts, could have minimal environmental impact.

Table 12 Maintenance frequency and environmental imapact

Maintenance Frequency	*Environmental Impact*
Rare (every few years)	Negligible—minor energy or material use

Potential Improvements: Developing more advanced coatings that extend the life of the galvanized layer or introducing designs that require even less maintenance can further enhance the sustainability of the structure.

. End-of-Life and Recycling

At the end of the rooftop structure's life cycle, recycling plays a critical role in minimizing environmental impact. Steel is one of the most recycled materials in the world, and the GI structure can be repurposed or recycled at the end of its life, reducing the need for new raw materials.

Table 13 End-of-Life and Recycling GI structure

Material	*Recyclability*	*Impact if Recycled*
Steel (Iron)	Highly recyclable (up to 90%)	Reduced need for new mining and smelting
Zinc Coating	Recoverable during steel recycling process	Lower environmental footprint with reuse

If improperly disposed of, however, the structure could contribute to waste, particularly through the zinc coating, which might leach into the environment. Recycling the GI structure recaptures much of the embedded energy from its production, making this stage critical for sustainability.

Potential Improvements: Designing the GI rooftop structure with easy disassembly in mind can facilitate more efficient recycling. Additionally, promoting recycling programs for end-of-life components can ensure that valuable materials are reused.

The Life Cycle Assessment of a GI rooftop structure for a 40kW solar panel system highlights both the environmental impacts and benefits at various stages. While the extraction and manufacturing of galvanized steel are resource-intensive, the long operational life of the structure and its recyclability at the end of its life significantly reduce its overall environmental footprint. Improvements in material sourcing, manufacturing efficiency, and recycling infrastructure can further enhance the sustainability of GI rooftop structures, making them a durable and eco-friendly choice for supporting solar energy systems.

Proposed model for environmental analysis and Thermal set point validation

The methodology involves developing a MATLAB-based computational model capable of processing four primary input variables to produce three essential output metrics. This analytical framework is tailored to handle varying load conditions and different levels of renewable energy generation, ensuring adaptability and relevance across various energy management scenarios.

Inputs and Outputs

Input Variables:

- **Forecasted Load (MW):** The predicted power demand for a specific time period.
- **Forecasted Renewable Generation (MW):** The estimated power supply from renewable energy sources.
- **Actual Load (MW):** The real-time power demand, dynamically ranging between 0 and 100 MW.

- **Actual Renewable Generation (MW):** The actual power output provided by renewable energy sources in real-time.

Output Metrics:

- **Thermal Set Point (MW):** The necessary thermal power output to balance the load demand.
- **Total Coal Saving (kg):** The amount of coal conserved as a result of utilizing renewable energy sources.
- **Total CO2 Emission Saving (kg):** The reduction in carbon dioxide emissions achieved through decreased coal usage.

Mathematical Formulation

The equations for calculating each output are defined as follows:
Thermal Set Point Calculation:

$$Thermal\ set\ point = \max\left(0, Actual\ load - Actual\ renewable\ generation\right)$$

This ensures that the thermal set point is non-negative, as a negative value would indicate excess renewable generation.
Coal Saving Calculation:

$$Total\ coal\ saving = Actual\ renewable\ generation * 429\ kg$$

This calculation is based on empirical data showing that 1 MW of renewable energy generation displaces approximately 429 kg of coal. [20-21]
CO2 Emission Saving Calculation:

$$Total\ CO2\ Emission\ Saving = Total\ Coal\ Saving \times 2.42\ kg$$

The coefficient 2.42 kg represents the average CO2 emitted per kilogram of coal burned .[22]

Analysis of Thermal Set Point

The thermal set point provides critical insights into the level of thermal power required after considering renewable energy generation. For instance, if the actual load is 80 MW and the actual renewable generation is 50 MW, the thermal set point becomes:

$$Thermal\ Set\ Point = 80 - 50 = 30\ MW$$

This implies that the thermal power plant must supply 30 MW to meet the total load demand. [23]

Coal Saving Potential

Renewable energy significantly reduces coal consumption. For example, if the actual renewable generation is 40 MW:

$$Total\ Coal\ Saving = 40 \times 429 = 17{,}160\ kg$$

This figure underscores the large amount of coal that can be saved through renewable integration .[24]

CO2 Emission Reduction

The CO2 emissions saved through reduced coal burning are substantial. Using the total coal saving from the previous calculation:

$$Total\ CO2\ Emission\ Saving = 17{,}160 \times 2.42 = 41{,}527.2\ kg$$

The reduction in emissions achieved through this approach aligns with global greenhouse gas (GHG) reduction targets, showcasing the significant environmental benefits of integrating renewable energy into power grids. The Intergovernmental Panel on Climate Change (IPCC) provides standardized carbon dioxide (CO_2) emission factors for stationary combustion within the energy sector, calculated using the low heat value (net calorific) method [25]:

- Lignite: 101,000 kg of CO_2 per terajoule (TJ)
- Subbituminous Coal: 96,100 kg of CO_2 per TJ
- Bituminous Coal: 94,600 kg of CO_2 per TJ
- Anthracite: 98,300 kg of CO_2 per TJ

These figures underscore the variability in CO_2 emissions based on the specific type of coal utilized in energy production, emphasizing the need for efficient management and a transition to cleaner energy sources [26].

Sensitivity Analysis

To validate the robustness of the model, simulations were run under varying scenarios:

- **High renewable generation**: Reduced thermal set point, increased coal savings.

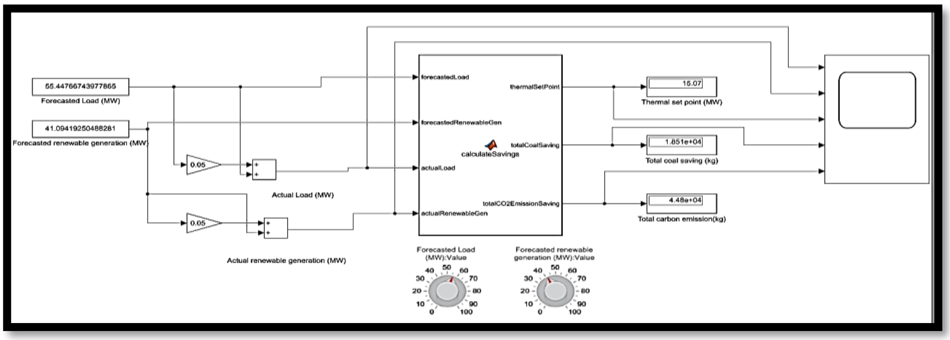

Figure 5 Higher renewable generation scenario

- **Low renewable generation**: Higher thermal set point, reduced coal savings.

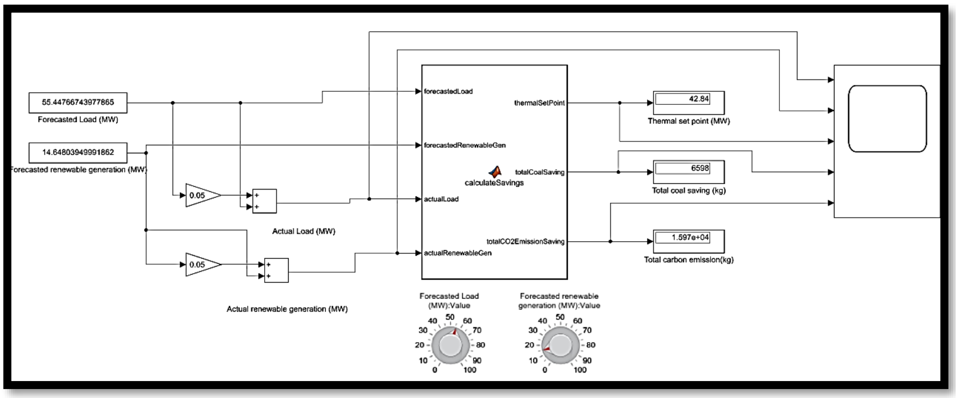

Figure 6 Lower renewable generation scenario

The analysis highlighted that as renewable penetration increases, the reliance on thermal power decreases, yielding higher environmental benefits.

Controller Design

The ANN-based controller takes two inputs:

- **Actual Load**
- **Actual Renewable Generation**

The controller generates the **Thermal Set Point** directly as its output. The ANN model was trained using historical data, with thermal set points from the MATLAB simulation used as target outputs during training. The ANN architecture includes:

- **Input Layer**: 2 nodes (Actual Load, Actual Renewable Generation).
- **Hidden Layers**: Fully connected layers optimized during hyperparameter tuning.
- **Output Layer**: 1 node (Thermal Set Point).
  ANN controller is shown in the figure below

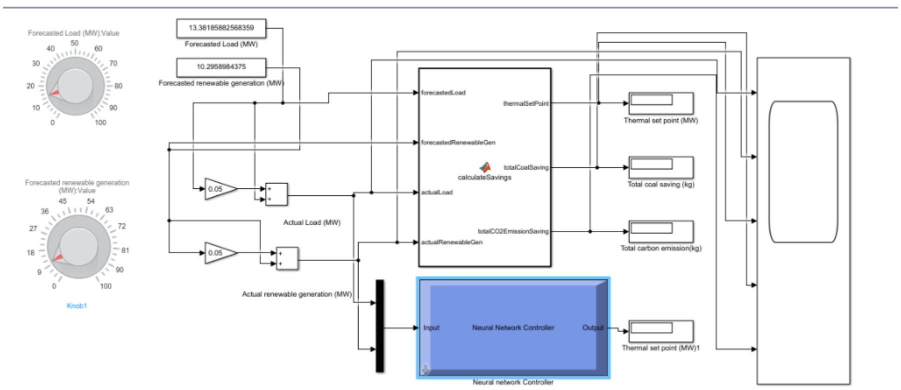

Figure 7 ANN controller prediction

Conclusion

The thermal set points calculated by the MATLAB model and the ANN controller were compared. Equivalency in outputs validates the ANN controller's reliability and accuracy.

The Life Cycle Assessment of the 40kW rooftop solar system installed in Majholi, Madhya Pradesh, demonstrates that while the initial production and installation phases have environmental impacts, these are significantly outweighed by the long-term benefits of clean energy generation. With an energy payback time of approximately 2.5 years and a substantial reduction in carbon emissions, the system proves to be an environmentally sustainable alternative to conventional power sources. The recyclability of key components further enhances its ecological value. This study highlights the importance of evaluating the entire lifecycle of renewable energy systems and suggests that advancements in solar technology, inverter efficiency, and integration with smart grid solutions can further improve their environmental performance and scalability in the future.

REFERENCES

1. Vishnu S Prabhu & Shraddha Shrivastava & Kakali Mukhopadhyay,, L ife Cycle Assessment of Solar Photovoltaic in India: A Circular Economy Approach, Springer, 2022
2. Vincenzo Muteri , Maurizio Cellura , Domenico Curto , Vincenzo Franzitta , Sonia Longo , Marina Mistretta, and Maria Laura Parisi , 'Review on Life Cycle Assessment of Solar Photovoltaic Panels', Energies, MDPI, 2020.
3. N Ranganath. 'Life Cycle Costing Analysis of Solar Photo Voltaic Generation System in Indian Scenario', International Journal of Sustainable Engineering Volume 14, 2021.
4. N. Leela Prasad, Life cycle assessment of 100 KWp Solar PV based electric PV generation system in India, Jan 2020, springer
5. Peishi Wu, Xiaoming Ma, Junping Ji, Yunrong Ma, 'Review on life cycle assessment of energy payback of solar photovoltaic systems and a case study', Elseveir 2017
6. Sharma, A., Mahajan, P. & Garg, R. End-of-life solar photovoltaic panel waste management in India: forecasting and environmental impact assessment. *Int. J. Environ. Sci. Technol.* **21**, 1961–1980 (2024). https://doi.org/10.1007/s13762-023-04953-2
7. Chybyung Park, Byongug Jeong, Peilin Zhou, Hayoung Jang, Seongwan Kim, Hyeonmin Jeon, Dong Nam, Ahmad Rashedi, Live-Life cycle assessment of the electric propulsion ship using solar PV, Applied Energy, Volume 309,2022,118477, ISSN 0306-2619,https://doi.org/10.1016/j.apenergy.2021.118477.
8. Abhishek Kumar, 'A review paper of solar in India', Gyancity Journal of Electronics and Computer Science Vol.3, No.1, pp.1-10, March 2018 ISSN:2446-2918 DOI: 10.21058/gjecs.2018.31001
9. https://www.legalentityidentifier.in/leicert/335800JVI2XZN5LED915/
10. https://www.ssmtd.info/
11. Fraunhofer Institute for Solar Energy Systems ISE. "Life Cycle Assessment of Photovoltaic Systems." Fraunhofer ISE, 2020.
12. International Energy Agency (IEA). "Solar PV Power Systems: Sustainability Report." IEA, 2021.
13. European Commission. "Environmental Impact of Transportation of Solar Panels." European Environment Agency, 2019.
14. NREL (National Renewable Energy Laboratory). "PV System Installation and Operation: Environmental Impact Overview." NREL, 2022.
15. Adani Solar. "Product Specifications and Performance of Adani 540W Solar Panels." Adani Solar, 2023.
16. Wambach, K., and Raugei, M. "End-of-Life Recycling of Solar Panels: Opportunities and Challenges." Journal of Sustainable Materials, 2021.
17. Fraunhofer Institute. "Recycling Potential of PV Systems: A Lifecycle Approach." Fraunhofer, 2020.
18. EnergySage. "Solar Panel Efficiency and Longevity." EnergySage, 2022.
19. PV Cycle. "Recycling and Recovery of Solar Panel Components: Industry Best Practices." PV Cycle, 2021.
20. He, Mingxin. (2024). Research on the Development of Thermal Power Engineering Based on Energy and Boilers. International Journal of Energy. 4. 11-14. 10.54097/xe2vpa14.
21. Mohamed Elwardany, A.M. Nassib, Hany A. Mohamed, Advancing sustainable thermal power generation: insights from recent energy and exergy studies, Process Safety and Environmental Protection, Volume 183, 2024, Pages 617-644, ISSN 0957-5820, https://doi.org/10.1016/j.psep.2024.01.039.
22. "2006 IPCC Guidelines for National Greenhouse Gas Inventories," Table 2.2 "Default Emission Factors for Stationary Combustion in the Energy Industries," page 2.16
23. R. E. Uhrig, "Introduction to artificial neural networks," Proceedings of IECON '95 - 21st Annual Conference on IEEE Industrial Electronics, Orlando, FL, USA, 1995, pp. 33-37 vol.1, doi: 10.1109/IECON.1995.483329.
24. Bolin Yu, Debin Fang, Feng Dong, Study on the evolution of thermal power generation and its nexus with economic growth: Evidence from EU regions, Energy, Volume 205, 2020, 118053, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2020.118053.
25. Kitey, Himanshu & Chandankhde, Pankaj & Jajulwar, Kapil & Mohammad, Shahnawaz & Shaikh, Mohammad Shahnawaz & Pragati, M & Fatinge,. (2024). Solar Power Generation Technique and its Challenges - A Comprehensive Review. GRENZE International Journal of Engineering and Technology. 01.GIJET.10.1.122.
26. M.S. Murshitha Shajahan, D. Najumnissa Jamal, V. Aparna, M.K.A. Ahamed Khan, Control of electric power generation of thermal power plant in TamilNadu, Case Studies in Thermal Engineering, Volume 12, 2018, Pages 728-735, ISSN 2214-157X, https://doi.org/10.1016/j.csite.2018.08.008.
27. Di Wang, Deying Liu, Chaonan Wang, Yunlong Zhou, Xiaoli Li, Mei Yang, Flexibility improvement method of coal-fired thermal power plant based on the multi-scale utilization of steam turbine energy storage, Energy, Volume 239, Part D, 2022, 122301, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2021.122301.
28. Avagianos, I.; Rakopoulos, D.; Karellas, S.; Kakaras, E. Review of Process Modeling of Solid-Fuel Thermal Power Plants for Flexible and Off-Design Operation. Energies 2020, 13, 6587. https://doi.org/10.3390/en13246587
29. Prakash, Surya & Sinha, Sunil. (2012). Load frequency control of three area interconnected hydro-thermal reheat power system using artificial intelligence and PI controllers. International Journal of Engineering, Science and Technology. 4. 10.4314/ijest.v4i1.4S.
30. Sriramula, Saraswathi and Reddy, B. Ravindranath and Kalavathi, M. Surya, Fractional Order Ann Controller for LFC of EVS Integrated Deregulated Power System (2020). International Journal of Advanced Research in Engineering and Technology (IJARET), 11(10), 2020, pp.13-27, http://www.iaeme.com/IJARET/issues.a, Available at SSRN: https://ssrn.com/abstract=3736043