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Renewable Energy Sourcing to Enhance Sustainable Manufacturing by Using Madhab's EEE Impact Analysis Model

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ABSTRACT

The world's increasing energy demand, coupled with the depletion of finite energy resources, necessitates a shift towards sustainable energy solutions. This research explores the multifaceted benefits of substituting conventional fossil fuel-based energy sources with renewable energy in industrial settings, with a focus on sustainable manufacturing. A case study was conducted at a printing and packaging factory in Bhubaneswar, Odisha, to analyze economic, environmental, health, safety, and efficiency factors associated with various energy options based on the Madhab's EEE (Environmental, Efficiency, Economic) impact analysis method. The study identified solar power generation as the optimal energy source, boasting the lowest EEE impact index of 1.90. Wind energy ranked second, followed by conventional GRID power and DG (Diesel Generator) power sources, which were found to be less favorable due to their higher EEE impact indices. Feasibility assessments revealed that the factory had ample rooftop and vacant land space for solar power plant installation, making it self-sufficient in power generation. The return on investment (ROI) for the solar power project was calculated to be 5.54 years, making it a viable option from a sustainability perspective. Moreover, the solar system could be integrated with the GRID through a reverse metering system, enabling excess energy to be sold back to the GRID. This research underscores the significance of transitioning to renewable energy sources in industries for environmental sustainability, energy security, and economic benefits. It emphasizes the need for similar studies in diverse industrial settings to identify the most suitable energy sources, considering all relevant factors.

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1. Introduction

In the contemporary era, the global and national policy landscape has prominently featured the pursuit of sustainable development, with a particular emphasis on addressing challenges posed by climate change and environmental degradation. At the forefront of this endeavor is the United Nations General Assembly's unveiling of a comprehensive framework known as the Sustainable Development Goals (SDGs). Established during a United Nations summit in New York, this framework comprises 17 goals and 169 targets, accompanied by an initial set of 330 indicators [1]. The SDGs serve as a guiding beacon, directing concerted efforts toward achieving a harmonious balance between social, economic, and environmental factors.

Effectively addressing critical issues such as climate change and the imperative transition to renewable energy requires a synchronized global monitoring and modeling effort [2]. The heightened stringency of pollution control regulations reflects a daily concern, underscoring the commitment to fostering a healthier environment for humanity [3]. In response to industries deviating from fair pollution control practices, pollution control boards have introduced online monitoring of emissions and effluent discharges from factories [4]. Consequently, renewable energy emerges as a viable and sustainable option, offering a pathway to alleviate challenges associated with pollution stemming from conventional energy generation sources. The quest for viable renewable energy sources gained significant momentum in the 1990s, driven by the escalating crisis of soaring oil prices [2]. This pursuit represents the definitive path forward for replacing fossil fuel-based energy sources with sustainable alternatives. The array of available alternatives includes bioenergy, direct solar energy, geothermal energy, hydropower, wind energy, and ocean energy. The adoption of these alternatives aligns with the broader global SDGs framework, serving as a pivotal means to attain environmental sustainability [2].

The introduction of the SDGs framework underscores the commitment to combating climate change and its 21st-century impacts, securing a sustainable future for generations to come [2]. The Sustainable Development Goals (SDGs) report [5] highlights the risks posed by climate change, emphasizing the potential erosion of decades of progress in addressing inequality, food security, and other SDGs. Within this context, the transition of the global energy system assumes paramount importance, as energy consumption stands as the primary driver of global greenhouse gas (GHG) emissions [6]. Shifting towards higher shares of renewable energy (RE) is identified as a key strategy for achieving universal access to clean, affordable energy, simultaneously reducing GHG emissions and mitigating water scarcity by eliminating freshwater consumption in thermal power generation [7].

This transition has already commenced, with renewables accounting for over 27% of global electricity generation by 2019, and an ambitious target of achieving 100% renewable energy in the near future [8]. Cost reductions have rendered renewable electricity increasingly competitive with conventional thermal power generation, with renewables even undercutting the operating costs of existing fossil and nuclear power plants in some regions [9].

A substantial portion of global energy consumption is attributed to industrial processes, underscoring the urgency of transitioning from fossil fuel-based energy sources to renewables within this sector. However, challenges such as capital costs, space requirements, information gaps, and access to raw materials impede the seamless adoption of renewable energy in industries. The efficient and economical utilization of solar and wind energy resources hinges on the optimal sizing of hybrid photovoltaic/wind systems [10]. The feasibility and cost-effectiveness of hybrid energy systems have become critical areas of global research. For instance, [11] delved into the economic, technical, and environmental performance of various hybrid power systems for powering remote telecom infrastructure [11, 12] endeavored to size an optimal PV-wind hybrid system by minimizing total costs while maintaining a predefined level of power supply reliability [12]. Dursun *et al*. [13] explored the feasibility of electricity generation from solar/wind hybrid systems in the remote Turkish city of Edirne, focusing on substantial fuel savings and the reduction of operating costs compared to standalone diesel systems.

The integration of wind and solar plants into hybrid systems has garnered substantial attention due to numerous advantages, as elucidated in various studies [14, 15]. Simulation-based research serves a dual purpose: to assess system feasibility and to estimate the system's lifecycle cost, encompassing installation and operational expenses over its lifespan [16-18]. Cost-benefit analyses have also been extensively conducted for wind and solar power sources [19-21].

Despite the considerable research on renewable energy systems, there is a notable gap in comprehensively addressing the specific benefits that industries can derive from transitioning from conventional energy sources to renewables. This paper seeks to fill this gap by thoroughly examining various energy sources applicable to a printing and packaging factory located in Bhubaneswar, Odisha. The analysis will consider factors such as price, environmental impact, and efficiency, with the ultimate aim of identifying the most suitable alternative energy source to replace existing fossil fuel-based systems. The primary focus will be on overcoming installation challenges and realizing the associated benefits. The alternative energy sources under consideration include power generation through DG sets, power generation through windmills, and power generation through solar power plants. Through this examination, the paper aims to provide valuable insights for industries contemplating a transition towards sustainable and renewable energy solutions.

2. Materials and Method

The study conducted on a printing and packaging industry located at Bhubaneswar, Odisha. The current energy requirement and supplying system has been studied. The renewable energy system i.e. solar power plant and wind meal etc. to fulfill the demand. EEE factor, as introduced by Madhab Chandra Jena *et al*. according to which the study was conducted for evaluation of available alternate energy sources.

In EEE impact factor first E refers to the Environmental Health and Safety impact, 2nd E refers to Efficiency or Effectiveness and 3rd E refers to Economic impact. The current energy source for running the factory is GRID power from Odisha State Electricity Board mostly generated from thermal power plant and around 10% power is generated through DG set which is kept as standby for GRID power supply.

3. Study on Factory Operation and Power Requirement

The factory spans across 8 acres and encompasses various operations, including raw material procurement, printing, value addition, cutting & creasing, folding & gluing, and dispatch of finished goods, as illustrated in Fig. (**1**). The primary raw materials for the factory include paperboard in sheet form and different colored inks used in the printing process for crafting packaging products. The printing operation employs high-speed sheet-fed offset printing machines. Following printing, the sheets undergo a value addition process, incorporating features like hot foil stamping, hologram stamping, lamination, etc. Subsequently, the sheets pass through cutting, creasing, and embossing machines to create profiled blanks suitable for final packet production. These blanks are then processed through the folder and gluer machine to produce the final output of packets. In the last stage, the packets undergo packaging in the CFCs, managed by the logistics department, before being dispatched to customers.

The existing power supply for factory operation is fulfilled by the GRID power from Odisha state Electricity Board and a DG Set of 800 KVA is installed for emergency power supply which supplies power in case of GRID power failure.

Daily Avg. energy requirement for running the factory = 5000 kWh

Yearly power requirement for running the plant = 1800000 kWh

For our study the data collected from the GRID power and DG set from the factory itself. The data related to solar power and wind power is collected from different sources.

4. Energy Sources Evaluation by Using Madhab's EEE Impact Analysis Model

As per Madhab's EEE impact analysis model the available energy sources need to be evaluated on the basis of Environmental impact, Economic impact and Efficiency impact. All the factors will be combining further to get the

EEE impact factor for different energy options and the best EEE impact factor would be considered for selection of energy supply source or energy sourcing.

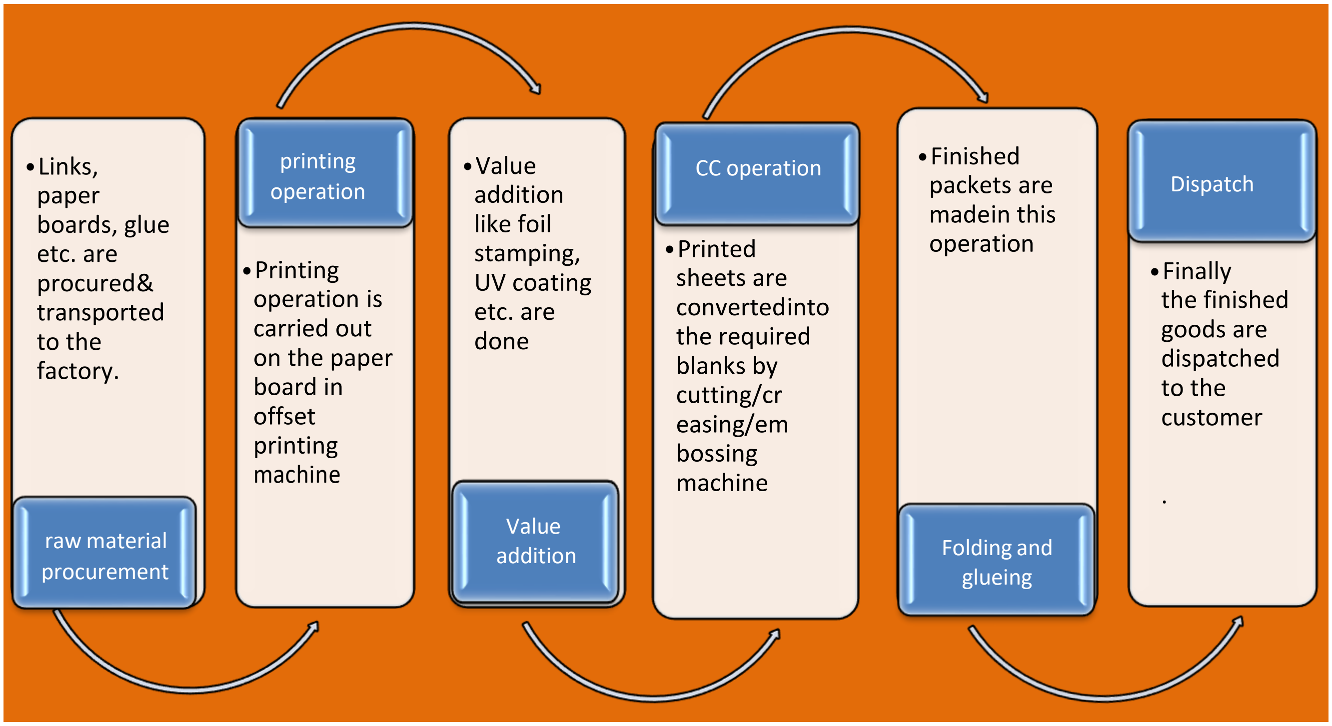

Figure 1: Process flow diagram of printing and packaging factory.

4.1. Environmental Impact of Different Energy Sources

The primary environmental impact of thermal power plants stems from air pollution caused by various pollutants and particulate matter released during the combustion of fossil fuels in boilers. The second source of environmental impact is fly ash collected from Electrostatic Precipitators (ESPs) and bed ash from the boiler firing bed. Boilers emit various pollutants and particulate matter through stacks, including Carbon dioxide (CO2), Nitrogen oxides (NOx), Sulfur dioxide (SO2), Carbon monoxide (CO), Formaldehyde, Polynuclear aromatic hydrocarbons (PAHs), Lead, Hydrogen Chloride (HCl), Cadmium, Mercury, Dioxin/furans, and other toxic chemicals [22, 23]. These pollutants contribute to climate change, acid rain, and the greenhouse effect, impacting both the environment and human health [24-26].

The safety impact of thermal power plants is significant, with inherent risks during plant operations, including instances of boiler explosions causing substantial loss of human life and property damage globally.

In contrast, the main environmental impact of DG power arises from air pollution, similar to automobiles, through the emission of pollutants and particulate matter from burning diesel in diesel engines. DG sets emit pollutants like Carbon dioxide (CO2), Nitrogen oxides (NOx), Sulfur dioxide (SO2), Carbon monoxide (CO), with minimal particulate matter through stacks. While DG sets pose no significant safety risk during power plant operations, their environmental impact includes climate change and acid rain.

On the other hand, solar power generation systems exhibit a low environmental impact, boasting a minimal carbon footprint compared to conventional power generation. Health and safety impacts are also lower than those associated with conventional power generation systems.

Similarly, wind power generation systems have a minimal environmental impact akin to solar power systems, with low health and safety impacts compared to conventional power generation. A detailed breakdown of different types of particulate matter and gaseous emissions is provided in Table **1**, while Fig. (**1**) visually compares the environmental impact, illustrating that GRID power has the highest impact, while solar power has the lowest.

Table 1: Environmental impact of different energy generation systems.

Fuel	PM Emission(gm/kWh)	Sox Emission(gm/kWh)	NOx Emission(gm/kWh)	Carbon Foot Print (Co2 gm/kWh)	Impact Index
GRID power (Coal)	4.1	7	0.428	980	4
Solar	0	0	0	40	1
Wind	0	0	0	11	1
DG set	0.03	3.5	0.5	850	2

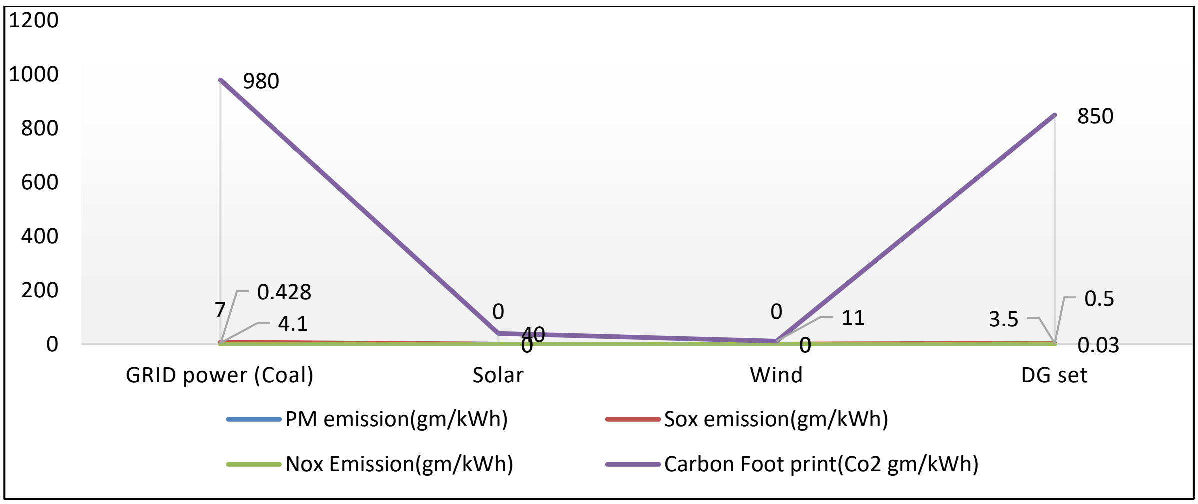

Figure 2: Environmental impact of different energy sources.

4.2. Generation Efficiency of Different Energy Sources

Setting aside factory efficiency, which remains constant for any energy supply, the primary consideration is the efficiency from input to output. Examining GRID power, predominantly generated from solar power plants, entails discussing various losses, including generation, transmission, and distribution losses.

On the other hand, focusing on DG power, primarily generated through diesel combustion, emphasizes generation losses, with transmission and distribution losses being negligible due to on-site power generation for the factory.

Solar power generation typically exhibits an efficiency range of 10 to 20%. Ongoing advancements in solar power panel technology are anticipated to further enhance efficacy in the future [27].

In the case of wind power generation, the efficiency ranges from 20 to 40%, as indicated by earlier studies [28]. Similar to solar power, advancements in the field are expected to improve power generation efficiency. Despite the lower efficiency of solar power generation, it is often considered as 100%, given its lack of direct user-supplied physical input. Fig. (**3**) provides a visual representation of different energy sources with varying generation efficiency.

4.3. Economic Impact of Different Energy Sources

Power generation involves burning fossil fuels, transmitting, and distributing the electricity to the end-user, with a cost of approximately 6 Rupees per unit.

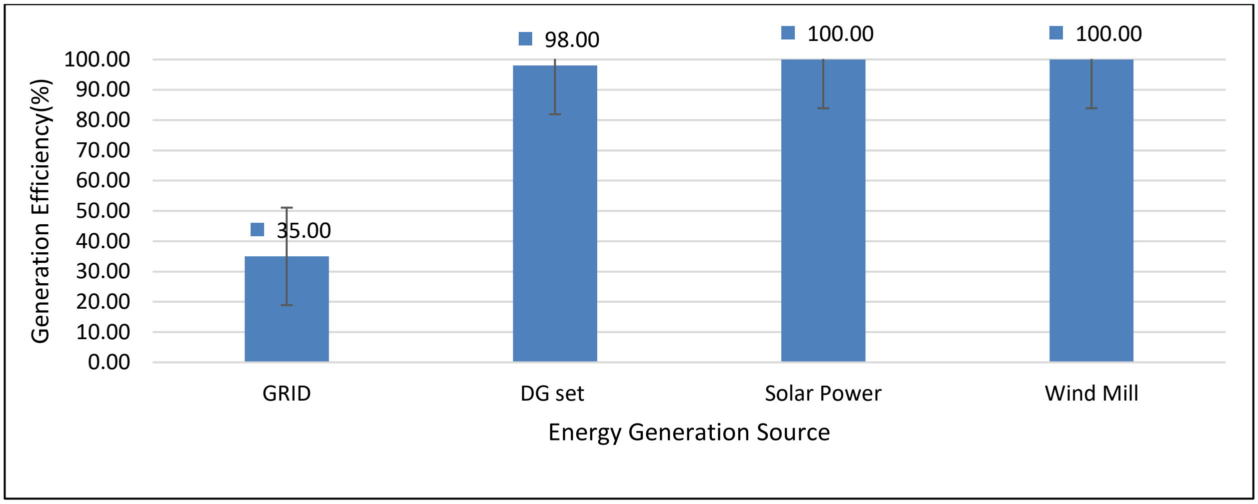

Figure 3: Generation efficiency of different energy sources.

In contrast, power generated by burning diesel in DG sets incurs significantly higher costs compared to other systems, ranging from 24 to 30 Rupees per unit in India.

Solar power, requiring no input materials for operation and converting solar energy into electricity, boasts a very low generation cost, attributed solely to installation and operational expenses.

Similarly, wind power generation, operating without input materials and converting wind energy into electricity, features a minimal generation cost, primarily associated with installation and operation. The economic impact of various energy sources is illustrated in Fig. (**4**).

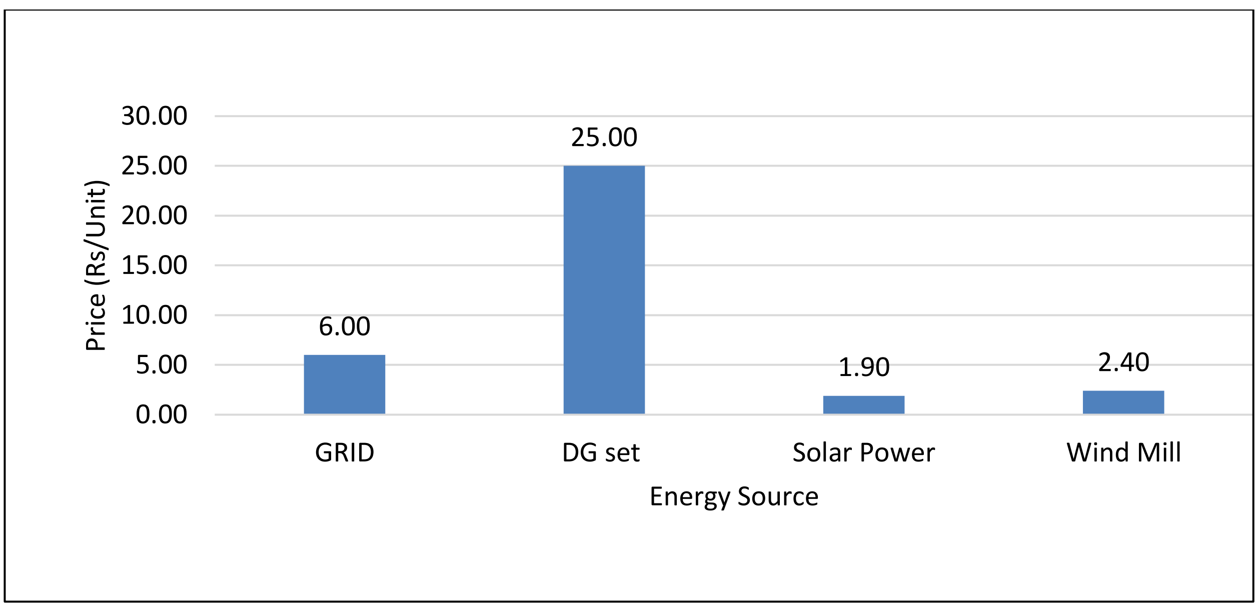

Figure 4: Economic impact of different energy sources.

4.4. EEE Impact Factor Analysis of Different Energy Sources

When we combine all the impacts i.e. environmental impact, generation efficiency impact and economic factor impact that is known as EEE impact. It is calculated and given in the Table **2** and the values are plotted in a graph given in the Fig. (**5**).

Table 2: EEE impact of Different Energy Sources.

Fuel	GRID	DG set	Solar Power	Wind Mill
Price Impact Index (Rs/ unit)	6.00	25.00	1.90	2.40
Efficiency impact	0.35	0.98	1	1
Environmental impact index	4	2	1	1
EEE impact Index	24.00	50.00	1.90	2.40

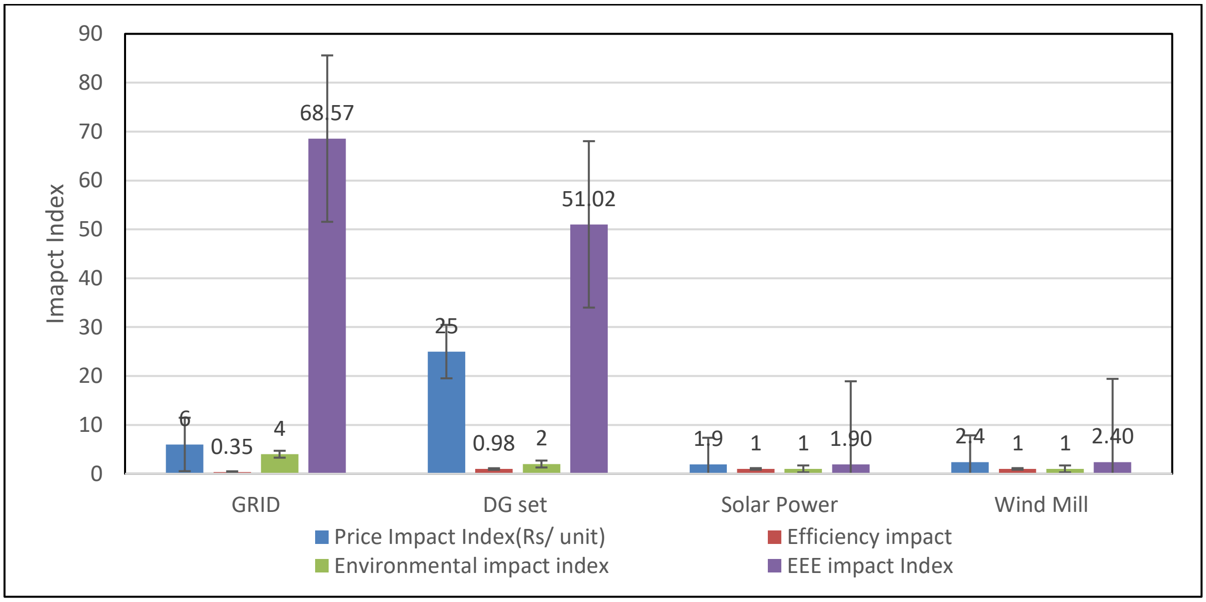

Figure 5: EEE impact factor energy sources.

5. Study on the Feasibility of Alternate Energy Supply to the Factory

The analysis considers three alternative energy sources for the factory: power supply from a DG set, power supply from wind energy, and power supply from a solar power plant. The feasibility study for each is outlined below:

5.1. DG Set Energy Feasibility Study

The addition of a DG set is feasible for power supply if required. However, the study reveals that DG power has the highest EEE impact index and a higher environmental impact compared to wind and solar power systems. Therefore, it is deemed unsuitable considering all factors.

5.2. Wind-Mill Energy Feasibility Study

Windmill energy is a better option than GRID power and DG sets, displaying a lower EEE impact index and environmental impact. Windmills can be installed offsite due to constraints in wind speed and space at the current location, making it a viable alternative.

5.3. Solar Power Feasibility Study

Solar power generation proves to be the best option among available sources, with the lowest EEE impact index and environmental impact. Further study is recommended for the installation of a solar power plant on the factory premises.

To determine the required system size for the solar power plant:

System Size in kW=Required units (kWh)CUF×365×24System Size in kW=CUF×365×24Required units (kWh)

System Size in kW=1,800,0000.19×365×24System Size in kW=0.19×365×241,800,000

System Size in kW=1081.47System Size in kW=1081.47

Total Power Output is calculated using the formula:

Total Power Output=Total Area×Solar Irradiance×Conversion EfficiencyTotal Power Output=Total Area×Solar Irradiance×Conversion Efficiency

Given that solar irradiance is 1000 Watt/m² and the conversion efficiency is 12%, the total area required is approximately 11,711.3 m², accounting for 30% clearance space.

To evaluate the Return on Investment (ROI):

ROI=Project Cost Annual Savings ROI=Annual Savings Project Cost

The estimated project cost is Rs 6.2 crores, and the annual savings are Rs 1.08 crores, resulting in an ROI of 5.54 years.

6. Results and Discussion

Based on the conducted study, the Solar Power Generation System emerges as the most favorable option, boasting an EEE index of 123 and excelling in economic, environmental, and efficiency factors. Windmill follows as the second-best choice. Conversely, the existing power sources from the GRID and DG set are not recommended due to unfavorable EEE factors and their negative impact on the environment, economy, and efficiency.

In the second part of the study, the assessment extends to the required power and space considerations. The factory, with approximately 8000 m² of rooftop space, proves suitable for solar power installation. Additional vacant land measuring 3711.3 m² can be utilized for the solar power plant, ensuring the factory's self-sufficiency in power generation and consumption.

Although the project's ROI stands at 5.54 years, which may not be exceptionally attractive, its implementation is advocated from a sustainability perspective. Furthermore, the system can be integrated with the GRID through a reverse metering system. This allows surplus power generated during low factory loads or shutdown periods to be fed back into the GRID, promoting an eco-friendly and economically.

7. Conclusion

The comprehensive study conducted on renewable energy sourcing for sustainable manufacturing, utilizing Madhab's EEE impact analysis model, provides valuable insights for the transition towards cleaner and more efficient energy solutions. The research focused on a printing and packaging factory in Bhubaneswar, Odisha, considering economic, environmental, health, safety, and efficiency factors associated with various energy options.

Solar power generation emerged as the optimal energy source, displaying the lowest EEE impact index of 1.90, followed by wind energy. In contrast, conventional GRID power and DG set power sources were deemed less favorable due to their higher EEE impact indices. Feasibility assessments revealed that the factory has sufficient rooftop and vacant land space for solar power plant installation, ensuring self-sufficiency in power generation.

The calculated Return on Investment (ROI) for the solar power project stands at 5.54 years, making it a viable and sustainable option. Furthermore, the integration of the solar system with the GRID through a reverse metering system enhances its economic and environmental benefits. The research underscores the significance of transitioning to renewable energy sources in industrial settings, emphasizing environmental sustainability, energy security, and economic advantages.

This study contributes to the broader understanding of renewable energy adoption in industries and highlights the need for similar assessments in diverse industrial contexts. As the global community continues to prioritize sustainable development goals, such research endeavors play a crucial role in guiding industries towards more responsible and eco-friendly energy practices.

Conflict of Interest

The authors declare no conflict of interest.

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