Journal of Harbin Engineering University
ISSN: 1006-7043

Vol 45 No. 6
June 2024

Carbon Emission Analysis of Off-Grid Standalone Integrated System for Residential/Commercial Loads

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Abstract
The world's most critical challenges centre around the depletion of fossil fuel reserves promote to discover solutions that preserve non-renewable resources and transition to renewable resources. Another critical issue revolves around the increasing levels of undesirable heat trapping gases like carbon dioxide, demanding urgent efforts to mitigate their impact. Renewable energy systems encompass technologies capable of generating electricity utilizing sources such as Wind, Solar, Hydroelectric, Biomass and other sustainable energy resources. Integrated systems introduce a perspective for the temporal alignment of intermittent renewable energy sources to model different power plant designs and subsequently analyse these designs to determine the most efficient configuration in terms of factors such as operational expenses, Net Present Cost (NPC), comparison of emissions and economic assessment. This work aims to design a reliable optimal system by integrating Diesel Generator (DG), PV system and battery to meet specific load demand of a residential loads and commercial load near Jawaharlal Nehru Technological University (JNTU), Hyderabad, Telangana, India. The optimized results provide four distinct categories findings. The suggested design of hybrid system with Solar PV and set of small Diesel generators which is equivalent to large rating along with converter and battery is found to be an economically efficient choice regarding operating costs and emissions of gases.

Keywords— Diesel Generator, Emissions, Integrated Energy System, Optimization, Renewable power

1. Introduction

Clean renewable energy presents a viable substitute for fossil fuels on a global scale. It incorporates various sources such as hydropower, wind, solar and biomass [1]. In response to growing concerns about energy security and climate change, the Indian government is actively reevaluating its energy policy to bring about significant changes. As per data from the Ministry of New and Renewable Energy (MNRE), in India the installed capacity of renewable energy from sources such as Wind, Solar, Small Hydro Power, Biomass and Waste to Energy excluding Large Hydro power, currently stands at 1,35,116MW with a notable rise from 35,449.59MW in the last ten years. The environmental damage is substantial due to the emission of greenhouse gases resulting from the use of traditional energy sources. Additionally, such energy reserves are finite and generating electricity from them comes at a high cost [2]. Renewable energy sources have shown to be a great alternative due to their environmental friendliness and reduced operating expenses. The only constraint in renewable energy sources is their transitory nature [3], which might be overcome by selecting the most appropriate combination to achieve an integrated system. As discussed in [4–6], integrating various sources of energy can give an environmentally friendly and dependable answer to the current power constraint crisis. HRES is a Hybrid Renewable Energy System refers to the combination of two or more sources of energy for the purpose of generating electricity, whether it operates independently or is linked to the grid [7]. The hybrid system tackles this issue by incorporating renewable energy sources into the grid mode, thereby guaranteeing a consistent and environmentally sustainable energy provision [8]. A combined energy system that utilizes wind, solar power, bio-energy and hydro-kinetic energy was designed by the authors [9]. The writers concluded that several combinations of various energy sources were going to be sufficient to meet the rising demand. The stand-alone hybrid production unit powered by battery storage devices was suggested by authors [10] as a way to store extra power from sources of renewable energy. When there is a shortage of electrical power from renewable sources, backup

measures like diesel generators or battery storage systems are utilized [11],[12]. Diesel fuel used in diesel generators plays a crucial role in powering the plant, constituting approximately 80% of the total energy costs in regions without reliable grid access or
with poor grid infrastructure [13]. Therefore, operators and owners of diesel generators need to evaluate factors such as design setup, operational procedures, maintenance, energy efficiency, emissions of greenhouse gases, and the lifespan of equipment [14]. In addition to aiding in the battle against climate change, particularly by reducing greenhouse gas emissions from electricity and heat production, photovoltaic (PV) power is positioned to play a critical role in the forthcoming shift from a centralized to a distributed generation model. Indeed, due to the easily scalable nature of small modular units used in PV power, the implementation of microgrids is now considered feasible and, in some instances, the most optimal solution. This is because PV power enhances the reliability of energy systems, reduces CO_2 emissions and electricity generation expenses, creates new job opportunities, and optimizes the utilization of local resources often overlooked in rural areas [14],[15] Diesel power plants, also known as engine-generators, emerge as a more viable option for supplying electricity to rural areas [15]. However, maintaining a low load factor, typically below 40-50% of the generator's capacity, proves inefficient and can result in a shorter lifespan for the generator, accompanied by increased maintenance expenses. Furthermore, incomplete combustion and the accumulation of carbon on cylinder walls accelerate engine wear, particularly during periods of light load operation due to lower combustion temperatures [15-18]. As a result, a hybrid diesel-PV power system, which integrates a PV plant with a diesel generator acting as a backup system to reduce the size of the PV components, provides intermittent power from the PV plant. This arrangement aims to minimize the operational time of generators, thus reducing fuel consumption, operational and maintenance costs, and replacement expenses. The generators are activated only when the demand exceeds a minimum load threshold [18-20]. Optimizing and simulating Hybrid Renewable Energy Systems (HRES) can now be accomplished using software tools available today, including Homer, iHoga and hybrid2, each offering diverse backgrounds and simulation capabilities. An Algorithm has been developed for optimizing and identifying the most viable system configuration to evaluate systems that are not connected to the grid as well as those connected to the grid for diverse applications, accomplished by HOMER as it helps to determine the optimal combination of PV, Wind, Hydro, Batteries, Biogas and Diesel Generators by inputting different variables. It identifies and excludes inefficient systems that cannot meet load demands in addition to sensitivity analysis to assess how different constraints impact the energy system [21] and offers the choice to define the operational lifespan of the power plant, allowing you to define the duration of its operational life [22]. Numerous literature reviews pertaining to the optimization [23-27] were reviewed. This paper addresses the application of renewable energy concepts for Residential and commercial loads to a particular region in India to formulate an optimized plan for a site at Jawaharlal Nehru Technological University Hyderabad (JNTUH), Telangana in India. The current work examines the significance of a hybrid setup comprising Photovoltaic (PV) panels, a Diesel generator and Battery system under the residential load and commercial load scenario.

2.

3. Site Selection and Load Profile

The selected area is JNTU Hyderabad region of Telangana State in India situated on the map at approximately 17°29′34″N 78°24′19″E. This area was chosen due to its significant potential for renewable energy sources, specifically solar which can be utilized independently in this region. The location of JNTU Hyderabad is indicated in figure 1.

Fig.1. Location of JNTU Hyderabad

Case-I

2.1. Residential Load Profile

The typical measurement for regular energy consumption stands at 11.26 kilowatt-hours per day, with a typical system demand of 0.47 KW. The maximum power demand is 2.09 KW, primarily due to chosen location having minimal energy needs. Load information is projected and averaged across the period of 24-hours to generate a profile of energy consumption as depicted in figure 2. Figure 3 and indicates monthly load profile and figure 4 indicates the annual load profile of residential load.

Fig.2. Daily Profile of Residential Load

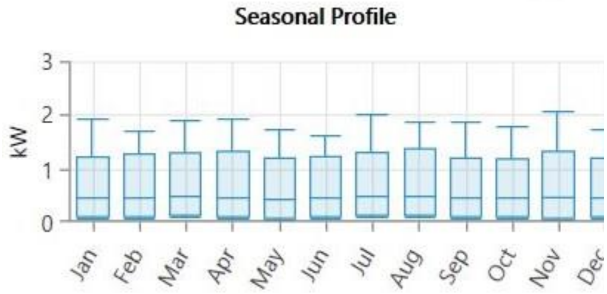

Fig.3. Monthly Profile of Residential Load

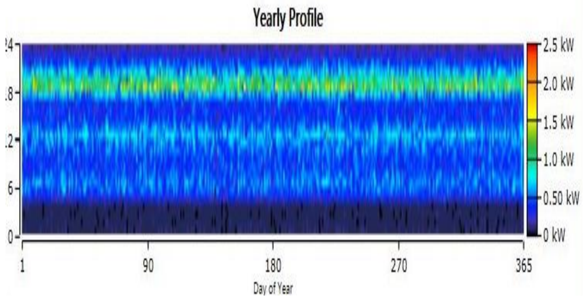

Fig.4. Annual Profile of Residential load

Case-II

2.2. Commercial Load Profile

The typical measurement for regular energy consumption stands at kilowatt-hours per day, with maximum power demand is 348.08 KW. Load information is projected and averaged across the period of 24-hours to generate a profile of energy consumption as depicted in figure 5. Figure 6 and indicates monthly load profile and figure 7 indicates the annual load profile of commercial load.

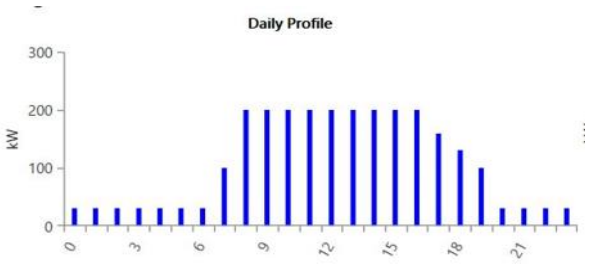

Fig.5. Daily Profile of Commercial Load

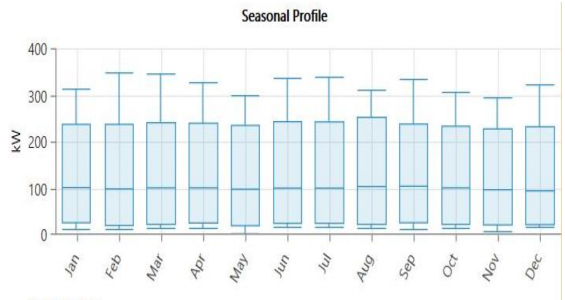

Fig.6. Monthly Profile of Commercial Load

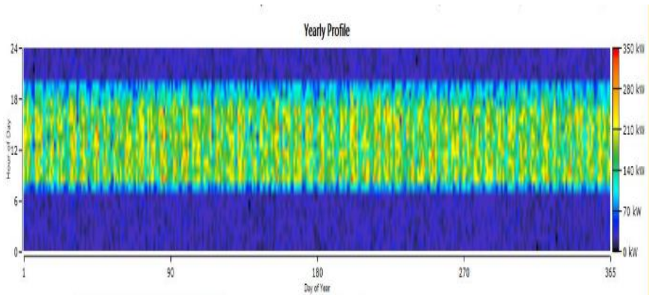

Fig.7. Annual Profile of Commercial Load

2.3. Solar Resource

Solar resource information provides data on the quantity of solar radiation reaching the surface of the Earth over a standard year. This functions as the input parameter for the Solar GHI (Global Horizontal Irradiance) Resource. Figure 8 illustrates Solar GHI Resource data displaying values in table 1 and corresponding graph depicting solar radiation intensity (measured in KWh/m^2/Day) for the entire year.

Fig.8. Solar GHI Resource Data

Table 1. Solar Radiation Intensity

Month	Clearness index	Daily Radiation (KWH/ m^2/day)
January	0.627	4.928
February	0.660	5.802
March	0.612	6.026
April	0.609	6.437
May	0.574	6.213
June	0.448	4.853
July	0.389	4.195
August	0.396	4.185
September	0.463	4.632
October	0.587	5.287
November	0.613	4.909
December	0.620	4.670

3. Existing Large Concentrated System Model

The existing hybrid system comprises a diesel generator, a PV array accommodating the load, solar modules, a converter, and batteries for energy storage. The electricity generated by the diesel generator is transmitted to the AC bus, where it undergoes conversion into DC power before distribution to the DC bus. Solar PV, serving as the DC power source is directly linked to the DC bus. Batteries are employed to store surplus electricity during daylight hours for subsequent use as the primary power source during night time periods. Figure 9 illustrates the block diagram representing the existing model of the large concentrated system.

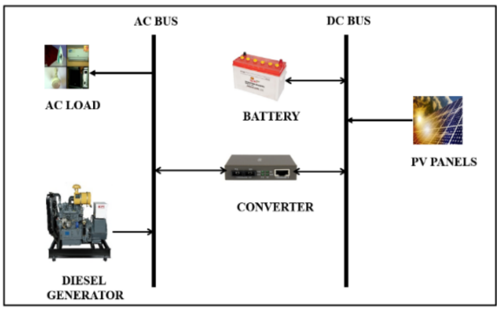

Fig.9.Block Diagram for Existing Large Concentrated System Model

To meet the energy demands of the residential area, a 10 KW Diesel generator is utilized, as shown in figure 10. In this arrangement, the electricity generated solely from the diesel generator is directly linked to the AC bus to supply power to the loads. Monthly electrical production from the Diesel generator for supplying loads of the residential area has shown in figure 11.

Fig.10. Residential Load fed with single 10KW Diesel Generator

Fig.11. Monthly Electric Production with single 10KW Diesel Generator for Residential Load

To meet the energy demands of the commercial load, a 500 KW Diesel generator is utilized, as shown in figure 12. In this arrangement, the electricity generated solely from the diesel generator is directly linked to the AC bus to supply power to the loads. Monthly electrical production from the Diesel generator for supplying commercial load demand has shown in figure 13.

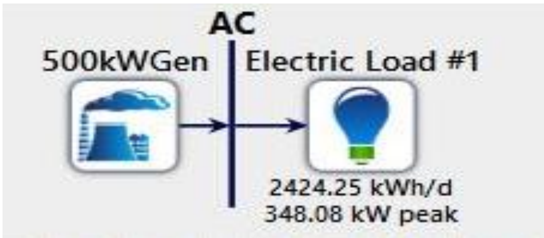

Fig.12. Commercial Load fed with single 500KW Diesel Generator

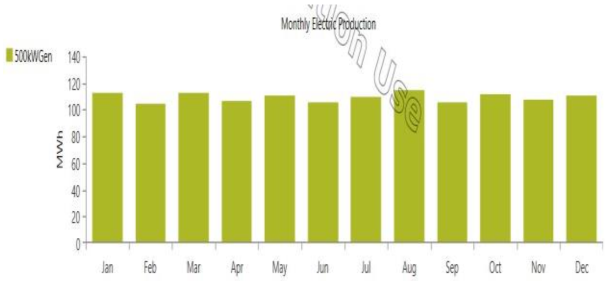

Fig.13. Monthly Electric Production with single 500KW Diesel Generator for Commercial Load

Fuel required to meet the load demand of Residential and commercial loads can be found by using the following equations:

F_{TGL}

$P_{TGL} = P_D$

$F_{TGL} = \alpha_L P_{TGL}^2 + \beta_L P_{TGL} + \gamma_L$ .... (1)

Where

F_{TGL} = Total Fuel consumption of one large diesel generator

P_{TGL} = Total power developed by one large diesel generator

P_D = Total power demand

α_L = quadratic constant

β_L = linear constant

γ_L = intercept constant

To minimize fuel consumption,lower operational and maintenance expenses, and decrease carbon emissions from the Diesel Generator, we are transitioning towards integrating the Diesel Generator with a Solar PV system. The integration involves combining Solar PV and Diesel Generator with converters and batteries to meet the demands of residential load. The schematic diagram and monthly electrical production of integrated system for residential loads is shown in figure 14 and figure 15 respectively.

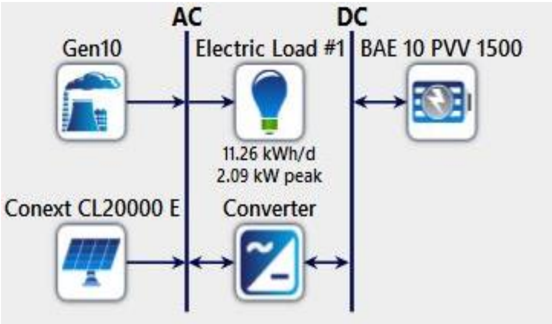

Fig.14. Residential Load fed with Solar and PV Integrated System

Fig.15. Monthly Electric Production with Integrated Solar PV system and Diesel Generator for Residential Load

The schematic for Solar PV and Diesel Generator Integrated system to meet the commercial load demand to reduce fuel consumption and monthly electrical production for such system is represented in figure 16 and figure 17.

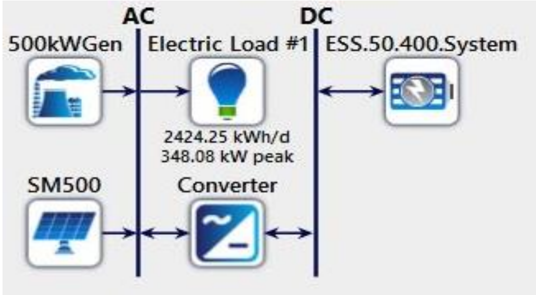

Fig.16. Commercial Load fed with Solar and PV Integrated System

Fig.17. Monthly Electric Production with Integrated Solar PV system and Diesel Generator for Commercial Load

4. Implementation Of Proposed Small Distributed System Model

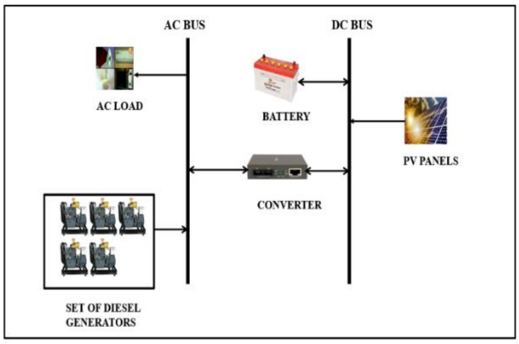

Fig.18.Block Diagram for Proposed Small Distributed System Model

The proposed hybrid system comprises a set of 5 diesel generators, a PV array supplying the load, a converter, and batteries for energy storage. The electricity generated by the 5-diesel generator is same as that of one large diesel generator but the fuel consumption is less compared to that of large diesel generator which causes reduction in cost incurred and

overall carbon emissions occurred. The electricity generated is transmitted to the AC bus, where it undergoes conversion into DC power before distribution to the DC bus. Solar PV, serving as the DC power source is linked to the DC bus which in turn is connected to a converter for power conditioning purpose. Batteries are employed to store surplus electricity during daylight hours for subsequent use as the primary power source during night time periods. Figure 18 illustrates the block diagram representing the proposed model of the small distributed system.
The proposal entails replacing a solitary 10KW Large Diesel Generator with five 2KW Small Diesel Generators for residential usage, as depicted in Figure 19 along with its monthly electrical production details in figure 20. Likewise, for commercial applications, a sole 500KW Large Generator is exchanged with five 100KW Diesel Generators, as shown in Figure 21 with its monthly electrical production pattern in figure 22.

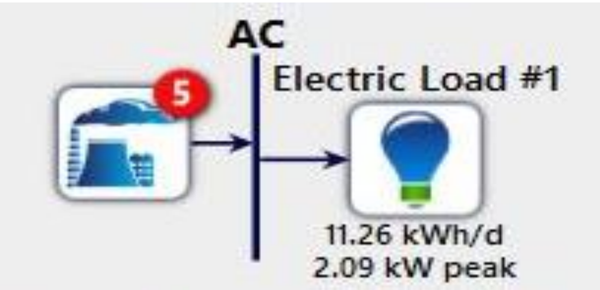

Fig.19. Residential Load fed with Five Diesel Generators

Fig.20. Monthly Electric Production for Residential Loads fed with Five 2KW Diesel Generators

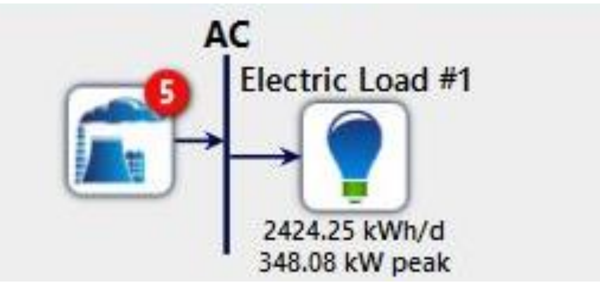

Fig.21. Commercial Load fed with Five 100 KW Diesel Generators

Fig.22. Monthly Electric Production for Commercial Load fed with Five 100KW Diesel Generators

Integrated system with small units of Diesel Generator, Solar PV system along with battery and converter for Residential load with its monthly electrical production is represented in figure 23 and figure 24 and Schematic with small units instead of large unit of Diesel Generator and PV system for commercial load with monthly electrical production details is represented in figure 25 and 26.

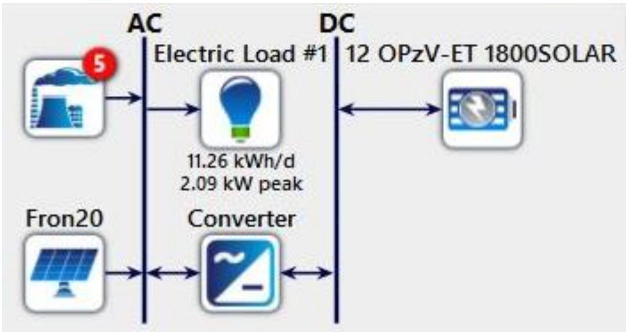

Fig.23.Residential Loads fed with Five Diesel Generators and PV Integrated system

Fig.24. Monthly Electric Production for Residential Loads fed with Five Diesel Generators and PV Integrated system

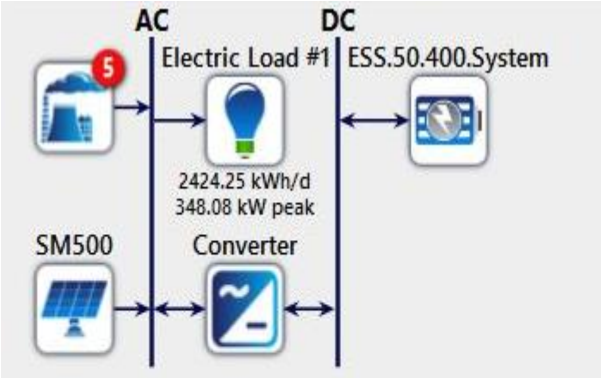

Fig.25. Commercial Load fed with Five 100 KW Diesel Generators and PV Integrated System

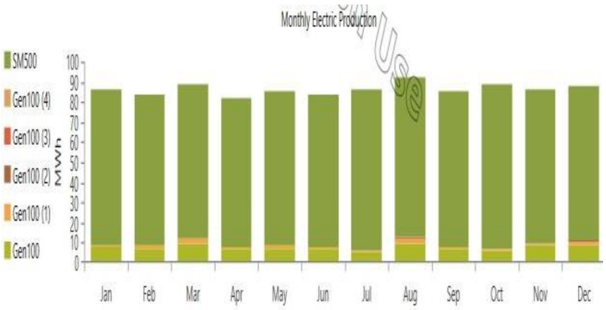

Fig.26. Monthly Electric Production for Commercial Load fed with Five 100 KW Diesel Generators and PV Integrated System

For Five small diesel generators

$F_{TGS} = \sum_{i=1}^{5} F_i$

$P_D = P_{TGS} = \sum_{i=1}^{5} P_{Gi}$

$F_i = \alpha_i {P_{gi}}^2 + \beta_i P_{gi} + \gamma_i$

$F_{TGS} = \sum_{i=1}^{5} \alpha_i {P_{gi}}^2 + \beta_i P_{gi} + \gamma_i$ .... (2)

$\alpha_i < \alpha_l$, $\beta_i < \beta_l$, $\gamma_i < \gamma_l$

$\sum_{i=1}^{5} \alpha_i {P_{gi}}^2 < \alpha_l {P_{TGL}}^2$

$\sum_{i=1}^{5} \beta_i P_{gi} \le \beta_L P_{TGL}$

$P_{TGS} = P_{TGL}$

$F_{TGS} < F_{TGL}$ .... (3)

Fuel consumed by set of small Diesel generators is less compared to Fuel consumed by large Diesel generator.

4.1. Solar Resource

Solar PV system converts solar radiation into solar energy to fulfill electricity needs. It operates primarily when there is sunlight and any surplus energy generated is stored in backup batteries. These batteries come in handy during night time when solar energy is unavailable, ensuring a stable power supply.

4.2. Converter

A converter is a device capable of converting a DC power source into AC through a process known as inversion or converts AC to DC through rectification. For this evaluation, a typical converter is employed with 95% effectiveness and 100% rectifier capability. Within this context, the optimizer determines the converter’s size to align with the requirements.

4.3. Diesel Generator (DG)

The inclusion of Diesel Generator in the Integrated system provides additional energy when the power demand cannot be fulfilled by renewable resources. Fuel costs differ in different regions due to shipping expenses. The price of diesel is considered as $1.0 per liter. Auto size Generator set is considered for the diesel generator analysis.

4.4. Battery

A standard rechargeable lead-acid battery with a nominal capacity of 1kWh and 12V specified voltage is considered in this proposed system. The battery boosts 80% roundtrip efficiency and can last up to a decade when its state of charge (SOC) ranges from at least 40% to up to 100%. The primary purpose of battery bank is to store surplus electrical power produced by the Renewable Energy Source (RES) network. It comes into play when the RES is unable to provide adequate energy to accomplish the demands of the load. Optimizer determines the appropriate size of the required Battery capacity.

5. Analysis of Results

5.1 Cost analysis for Residential and Commercial loads

Various power plant configurations are analysed and simulated to determine the most optimized setup based on factors such as Levelized Cost of Energy (LCOE), Operating costs, Net Present Cost (NPC), Emissions and economic comparisons. In accordance with the hundreds of simulated scenarios, considering input settings and sensitivity levels with reduced net present cost for Residential and commercial loads has shown in figure 27 and figure 28 respectively for different configurations of proposed power generation system. Table 2 and Table 3 gives detailed cost comparison of proposed system for Residential and commercial loads with different configurations.

Cost of the system is function of total fuel consumption and is given as

Cost = f (F_T) ...... (4)

from equation (3) & (4)

$\text{Cost}_{(\text{TGS})} < \text{Cost}_{(\text{TGL})}$

Where,

$\text{Cost}_{(\text{TGS})}$ = Cost of a single small diesel generator

$\text{Cost}_{(\text{TGL})}$ = Cost of a single Large diesel generator

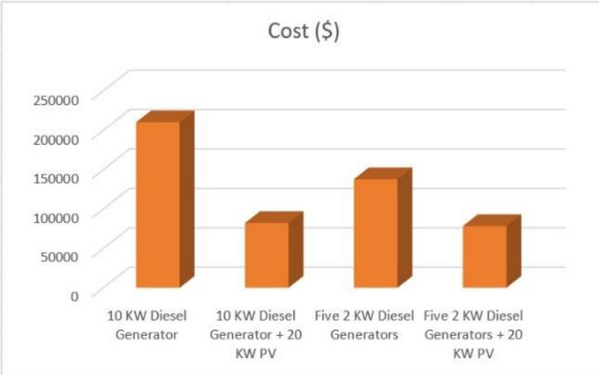

Fig.27.Cost analysis of Residential load

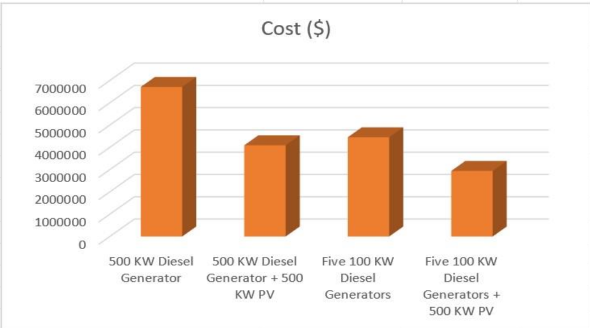

Fig.28.Cost analysis of Commercial load

5.2 Carbon Emission analysis for Residential and Commercial loads

The primary contributors to global climate change, such as sulphur dioxide, nitrogen dioxide and carbon dioxide, have gained considerable international focus. Among these gases, carbon dioxide is acknowledged as the predominant gas that has paved a way to explore methods for reducing and mitigating carbon. Energy sector, a significant contributor to carbon emissions, is actively striving to reduce its carbon output and advocate for carbon- efficient alternatives. working to reduce carbon output and promote low-carbon electricity in alignment with carbon peak and carbon-neutral targets. Integrated Energy System (IES) plays a pivotal role in achieving these objectives with its high energy efficiency, it is expected to be the central focus of environmentally friendly power in the times to come. System that integrates energy serves as an efficient approach to limit carbon emissions by coordinating and strategically planning diverse sources of energy. The suggested unified system includes a model for allocating optimally with multiple objectives focused on minimizing the total annual cost and carbon emissions, aiming to achieve both environmental and economic benefits. Figure 29 and Figure 30 depicts the analysis of carbon emissions for Residential and commercial loads for different configurations of a proposed system. Table 2 and Table 3 provides a comprehensive comparison of emissions for the proposed system across residential and commercial loads, considering various configurations.

Emissions of the system are function of total fuel consumption and is given as

$C_{Emissions} = f(F_T)$ ...... (5)

from equation (3) & (5)

$C_{\text{Emissions(TGS)}} < C_{\text{Emissions(TGL)}}$

Where,

$C_{\text{Emissions(TGS)}}$ = Carbon emissions from a set of small diesel generators

$C_{\text{Emissions(TGS)}}$ = Carbon emissions from a single large diesel generator

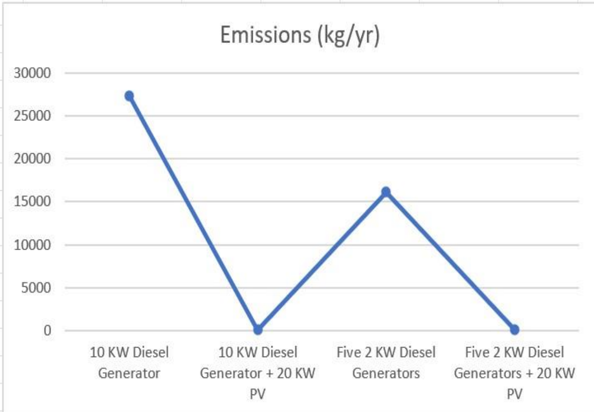

Fig.29.Emission analysis for Residential load

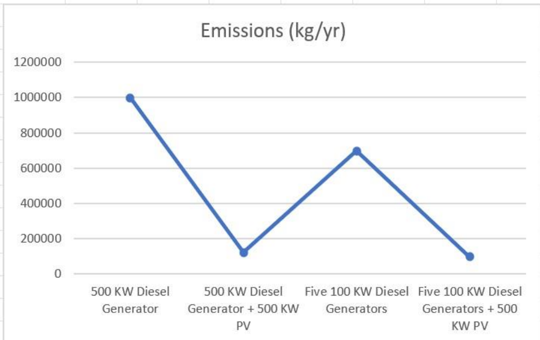

Fig.30.Emission analysis for Commercial load

Table 2: Comparison of Emissions and Cost between Existing large concentrated model and proposed small distribution model for Residential Loads

	Residential Load	Residential Load

	1 Diesel Generator (10KW)	5 Diesel Generators	5 Diesel Generators	5 Genera + PV
Emissions (kg/yr)	27,348	16,110	43.7	25.4
Cost ($)	2,10,095	1,37,910	82,211	78,295

Table 3: Comparison of Emissions and Cost between Existing large concentrated model and proposed small distribution model for Commercial Loads

6. Conclusions

The objective is to evaluate the different combinations of proposed power generation system for scaling down CO_2 emissions and to minimise Net Present Cost (NPC). Generated Electrical output, load demand and consumption of load details are examined after conducting a thorough analysis of the obtained outcomes. The integrated system, incorporating both PV panels and a cluster of Diesel Generators with reduced ratings equivalent to that of a solitary large Diesel generator, along with batteries and converters, presents the optimal solution for fulfilling the energy demands of both residential and commercial loads. This approach excels in cost reduction and carbon emission mitigation compared to other options, such as using a single large Diesel generator, employing multiple small diesel generators to fulfill load requirements, or integrating a large Diesel generator with Solar PV technology. The results emphasize a substantial reduction from 27,348 kg/yr to 25.4 kg/yr in emissions for Residential loads and 9,98,862 kg/yr to 95,052 kg/yr for commercial loads accompanied by a significant limiting in operational expenses from $2,10,095.60 to $78,295.61 for Residential loads and $67,14,420 to $29,45,254 for commercial loads annually in contrast to a Diesel Generator system of large rating that operates independently.

	Commercial Load		Commercial Load	
	1 Diesel Generator	5 Diesel Generators	1 Diesel Generator + PV	5 Diesel Generators + PV
Emissions (kg/yr)	9,98,862	6,96,144	1,20,501	95,052
Cost ($)	67,14,420	44,55,117	40,95,920	29,45,254

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