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RESEARCH ARTICLE **RENEWABLE ENERGY**

Grid Reliability Enhancement via PV-Diesel Hybrid System in Palestine: Load Flow Analysis and CO_2 Assessment

Wael A. Salah[1,*], Anees Abu Sneineh[1], Mohamed Elnaggar[2], Hala J. El-Khozondar[3,4], Yasser F. Nassar[5], Alfian Ma'arif[6], Mohammed J.K. Bashir[7], Mai Abuhelwa[8]

[1]Department of Electrical Eng., College of Eng. and Technology, Palestine Technical University - Kadoorie, Tulkarm, Palestine.
[2] Engineering Professions Department, Palestine Technical College – Deir El-Balah, Gaza Strip, Palestine
[3] Electrical Engineering and smart systems Department, Islamic University of Gaza, P. O. Box 108, Gaza, Palestine
[4] Department of Materials and London Centre for Nanotechnology, Imperial College London, UK
[5] Mechanical engineering and renewable energies Dept., Wadi AlShatti University, Brack, Libya
[6] Electrical Engineering Department, Industrial Technology Faculty, Universitas Ahmad Dahlan, Yogyakarta, Indonesia
[7] School of Engineering & Technology, Central Queensland University, 120 Spencer St., Melbourne, QLD 3000, Australia
[8] Department of Electrical Engineering and Computer Science, University of Missouri, Columbia, Missouri, USA

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A B S T R A C T

Since the majority of Palestine's electrical demands are met by imports, the country continues to struggle with energy supply security. Additionally, as cities and populations grow, so does the need for electricity, which results in frequent power outages that affect daily living and economic growth. In order to overcome this obstacle and improve energy security in the town of Ya'bad, a hybrid energy system that integrates diesel generators with solar photovoltaic systems is modeled using different power system analysis and management tools including MATLAB, ETAP and SCADA. In order to alleviate the scarcity of imported electricity, the management system was put into place in collaboration with the Ya'bad Electricity Company. The proposed system involves the design and implementation that combines solar cells and diesel generators. Solar cells are integrated into the electricity grid, thus providing an additional source of power. In the event of power outages or shortages of imported energy, diesel generators are activated to ensure a continuous electricity supply. This integrated approach improves the capacity of the electricity grid and also enables compensatory power generation via solar cells, mitigating the impact of reduced electricity consumption. The peak demand requirements met by diesel generators is 8247.77 kW. Whereas the environmental advantages were achieved by reducing carbon dioxide emissions of 12,185 tons of CO2. Therefore, the system provides a sustainable strategy for enhancing energy reliability. As well, establish a robust and self-sufficient infrastructure for supplemental energy, reducing reliance on imported sources and promoting energy sustainability.

تحسين موثوقية الشبكة الكهربائية عبر نظام هجين يعمل بالطاقة الشمسية والديزل في فلسطين: تحليل تدفق الأحمال وتقييم انبعاثات ثاني أكسيد الكربون

وائل صلاح[1،*]، أنيس أبو سنينة[1]، محمد النجار[2]، هالة الخزندار[3،4]، ياسر نصار[5]، ألفيان معارف[6،*]، محمد بشير[7]، مي أبوحلوة[8]

الكلمات المفتاحية

هجين
إدارة الطاقة
الخلايا الكهروضوئية
مولدات الديزل
الاستدامة
موثوقية الشبكة
تحليل تدفق الأحمال

الملخص

نظراً لأن معظم احتياجات فلسطين من الكهرباء تُلبى عن طريق الاستيراد، لا تزال البلاد تعاني من أزمة أمن الطاقة. إضافةً إلى ذلك، ومع نمو المدن وتزايد عدد السكان، يزداد الطلب على الكهرباء، مما يؤدي إلى انقطاعات متكررة للتيار الكهربائي تؤثر على الحياة اليومية والنمو الاقتصادي. للتغلب على هذه العقبة وتحسين أمن الطاقة في مدينة يعبد، تم تصميم نظام طاقة هجين يدمج مولدات الديزل مع أنظمة الطاقة الشمسية الكهروضوئية باستخدام أدوات تحليل وإدارة أنظمة الطاقة المختلفة، بما في ذلك MATLAB وETAP وSCADA. وللتخفيف من ندرة الكهرباء المستوردة، تم تطبيق نظام الإدارة بالتعاون مع شركة كهرباء يعبد. يتضمن النظام المقترح تصميم وتنفيذ نظام يجمع بين الخلايا الشمسية ومولدات الديزل. تُدمج الخلايا الشمسية في شبكة الكهرباء، مما يوفر مصدراً إضافياً للطاقة. وفي حالة انقطاع التيار الكهربائي أو نقص الطاقة المستوردة، يتم تشغيل مولدات الديزل لضمان استمرار إمدادات الكهرباء. يُحسّن هذا النهج المتكامل قدرة شبكة الكهرباء، كما يُتيح توليد طاقة تعويضية عبر الخلايا الشمسية، مما يُخفف من أثر انخفاض استهلاك الكهرباء. تبلغ ذروة الطلب التي تُلبّيها مولدات الديزل 8247.77 كيلوواط. في حين تحققت المزايا البيئية من خلال خفض انبعاثات ثاني أكسيد الكربون بمقدار 12185 طنًا. لذا، يُوفّر هذا النظام

*Corresponding author
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استراتيجية مستدامة لتعزيز موثوقية الطاقة، بالإضافة إلى إنشاء بنية تحتية قوية ومكتفية ذاتيًا للطاقة التكميلية، مما يُقلل
الاعتماد على مصادر الطاقة المستوردة ويُعزز استدامة الطاقة.

Introduction

In today's world, energy is the very essence of life [1-3]. The optimal use of energy is a crucial factor for many countries [4-11], especially those suffering from scarce natural resources [12-14]. Political and economic fluctuations, coupled with the instability of oil supply chains, have led many nations to adopt sustainable energy solutions [15-19]. However, many countries have yet to fully or even partially implement these systems due to numerous economic and geopolitical obstacles [20-26]. As well as challenges related to the availability of infrastructure and the necessary infrastructure [27-31].

The use of renewable energy sources is increasing worldwide [28, 32-35]. This continued expansion led to a significant milestone in 2024, when clean electricity accounted for more than 40% of total global energy production [36-38]. This shift reflects an accelerated deployment of technologies such as solar and wind power, representing tangible progress towards reducing carbon emissions in the electricity sector and lessening reliance on fossil fuels [39-44]. Despite the 2020 coronavirus pandemic, the global development of renewable energy continued unabated, resulting in the advancement of clean energy opportunities and challenges in the direction of increased adoption [45, 46]. Renewable energy (RE) investments approached the $2 trillion barrier for and keeps rising [47, 48]. As a result of awareness and preservation of the environment and natural resources and pollution problems resulting from fossil fuel sources [13, 14, 49], in addition to the increase in fossil fuel prices [50, 51], energy producers have turned to renewable energy sources and continue to rely on them [52-54].

The global electricity generation in 2024 reached approximately 30,850 TWh (30.85 PWh), with fossil fuels (coal, gas, oil) providing about 58%, renewables (hydro, wind, solar, bio, geo) around 32%, and nuclear around 10% [38]. Driven by concerns about climate change and global warming, the global installed capacity of renewable energy grew by 50% in 2024. In the end of 2025, the global installed capacities of renewables such as solar, wind, hydropower, geothermal, marine, biogas, etc reached about 4,448.1 GW, from them 2,200 GW for PV solar energy systems. This growth in the RE market reflects a global shift towards renewable and sustainable energy technologies [55, 56].

In 2025, there was a significant increase in energy demand for all fuel types. Renewable energy technologies, chiefly solar photovoltaic power, were the predominant contributors, succeeded by natural gas as shown in Figure 1. Renewable and nuclear energy sources constituted approximately 60% of the overall increase in global energy demand, with electricity generation from these sources surpassing the total rise in electricity demand.

The most famous of these sources are solar energy systems and wind turbines [57-60]. To overcome these challenges, renewable energy sources have been relied on continuously, and solar energy has become the most widely used energy source in the world due to its simple cost, ease of transportation, and simplicity of installation and implementation [56, 61-63]. The efficiency of the solar energy system can be improved by integrating it with storage batteries or diesel generators [64-66]. Thus, achieving energy independence and not being completely dependent on the main source [67, 68]. The integrated use of different energy sources, combining traditional energy with more widely used renewable energy sources such as solar and wind power, or often using natural gas as an alternative to fossil fuels, remains a solution to overcome shortages and the unreliability of electricity and power supply [69-71].

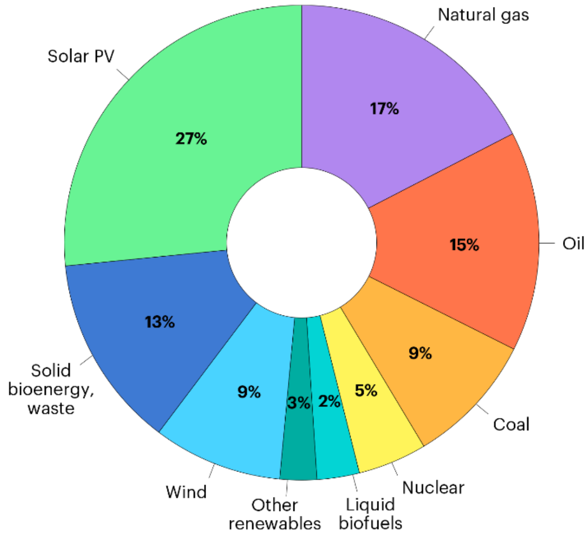


Figure 1: The share of energy demand growth by source. Source: IEA **[72]**, licensed under CC BY 4.0

Palestinian Territories generated less than 10% of its electricity demand [73]. With the population growth in Palestine, and the rapid increase in living standards and industrial production in Palestine, the country needs a significant amount of electricity per year [74]. This caused a tremendous demand on electricity in Palestine. Palestine is considered an occupied state; it mainly relies of electricity imported from the Israeli company Israel Electric Corporation (IEC). This represents the remaining 90% of the aforementioned electricity demand. The Palestinian economy's development is impeded by the monopoly on electricity generation, which is associated with geopolitical conditions. It causes instability in the electricity supply. The Palestinian Electricity Company serves as the primary electricity supplier for the Palestinian territories due to the region's restricted hydrocarbon and natural gas production.

There is a growing trend towards integrating more renewable energy sources into electricity grids. This includes microgrids that can operate in both grid-connected and standalone modes [75]. These grids are characterized by a high level of distributed power generation. There is also a need to improve power quality and reduce energy losses [10, 76, 77].

One of the main and direct responses to these challenges, is to use integrated solar system (full package of batteries, solar cells, cables … etc.). However, this solution has some disadvantages, like high batteries prices, relatively less reliable, exponentially decay in batteries lifetime [78]. Another solution which replaces the batteries with fuel generators, called solar-fuel hybrid system, which is a setup that integrates both solar energy technologies, such as solar panels, with conventional fuel-powered systems, such as internal combustion engines [79, 80]. This combination allows for more reliable and sustainable power generation by harnessing both renewable solar energy and traditional fuel sources.

The shift to renewable energy sources and decentralized generation systems aims to increase the share of renewable energy sources in the overall energy mix to more than 50% by 2050 [67]. This will be achieved through the design of a hybrid renewable energy system that combines photovoltaic cell and wind turbine technologies, supported by a hydroelectric energy storage system [81, 82]. Hybrid renewable energy systems, which integrate sources such as wind power and solar photovoltaic energy, offer a more consistent and uninterrupted energy supply than single-source systems [8, 58, 67, 81, 83-89].

In order to attain sustainable electricity independence in Palestine, this research aims to identify a solution to the energy shortage. In general, the Palestinian electricity sector encounters a multitude of obstacles as a result of its dependence on electricity imported from the Israeli Electric Corporation. Ya'bad, a Palestinian community located near Jenin, is currently experiencing a severe electricity shortage, as evidenced by the frequent power outages that residents have reported. The town's acute scarcity is the result of its reliance on the Israeli company's supply and the absence of independent generators. These issues are further exacerbated during the summer months as a result of the insufficient supply and increased demand to satisfy household requirements. Frequent power outages are the result of the unstable electricity supply and high energy consumption. Therefore; the main objectives of this research could be summarized as: Objectives of this study

1. Improving system efficiency by combining solar energy with fuel-powered systems. Solar energy can supplement the energy deficit of fuel-generated power, reducing the amount of fuel needed to generate the same amount of energy.
2. Enhance energy security throughout diversifying energy sources using hybrid systems. Less reliance on a single energy source can be particularly beneficial in areas with unstable fuel supplies.
3. Reducing energy costs as solar energy is free once the infrastructure is in place. Therefore, combining it with fuel-powered systems will lead to long-term savings in fuel consumption costs.
4. Reducing harmful carbon emissions as solar energy is renewable and produces no greenhouse gases during operation. By integrating solar energy into hybrid systems, overall carbon emissions and their environmental impact can be reduced.

This research addresses the shortage of electrical power and seeks practical pathways toward sustainable electricity independence in Palestine. The proposed solution adopts a hybrid energy system based on the integration of photovoltaic generation with diesel generators to enhance supply reliability and mitigate power interruptions in the town of Ya'bad near Jenin.

Methodology

This section presents details of the modeling and study of a project to add diesel generators integrated with solar power generation plants. The proposed model utilizes priority information to integrate diesel generators with solar power stations in Ya'bad city in Jenin governorate. The process includes data acquisition, load analysis, selection of diesel generators, and simulation to ensure optimal performance and reliability using simulation design tools as shown in Table 1.

This simplified method entails a data-driven selection and integration process that employs historical load data and simulation tools to design an efficient hybrid power system. In order to guarantee the seamless integration of solar power plants with diesel generators, a load analysis was implemented. The loads were subsequently analyzed to identify peak load hours and assess critical hours in order to ascertain the number of generators necessary for the system configuration. Additionally, the calculations associated with the integration of solar power plants with diesel generators were examined. In order to ascertain the nature of the loads, the quantity of power required from the diesel generators, and the number of generators necessary to supply the required electricity, a review of the calculations was conducted. The primary flow of analysis and calculations for the proposed power system in the city of Ya'bad, Palestine, is depicted in the accompanying Figure 2.

The data was obtained from the Ya'bad electricity authority. In addition to the data measurements at the connection point with the company Israel Electric Corporation (IEC), the requisite data was obtained to implement and execute the simulation for five solar power generation stations. The plan, which shows the distribution of electrical loads in Ya'bad city, was obtained from the ETAP program. The plan will be used to select the most critical locations for the addition of diesel generators.

Figure 3 shows the schematic diagram of the hybrid energy system proposed for Ya'bad city that integrate the photovoltaic generation, diesel backup, and an energy management strategy (EMS) for reliable electricity supply, optimize operation under varying conditions, and mitigating the CO_2 emissions.

The MATLAB tool is used to analyze the nature of the electrical network loads and choose the critical points, the highest loads and the least generation of solar energy. In addition, to estimate the average load, peak load, base load and load factor. MATLAB utilized to obtain the load charts to detect the critical times of the year. As well obtain a chart for the four seasons to

Table 1: Simulation design tools for robust and efficient hybrid power system

Section	Description	Tools Used
Data Acquisition	Collection of solar power data and electrical load distributions.	SCADA system
Load Analysis	Analysis of load characteristics and identification of critical points for generator integration.	MATLAB
Generator Selection	Selection of appropriate diesel generators based on load analysis and market availability.	research
Simulation and Monitoring	Use of ETAP for system simulation and monitoring.	ETAP

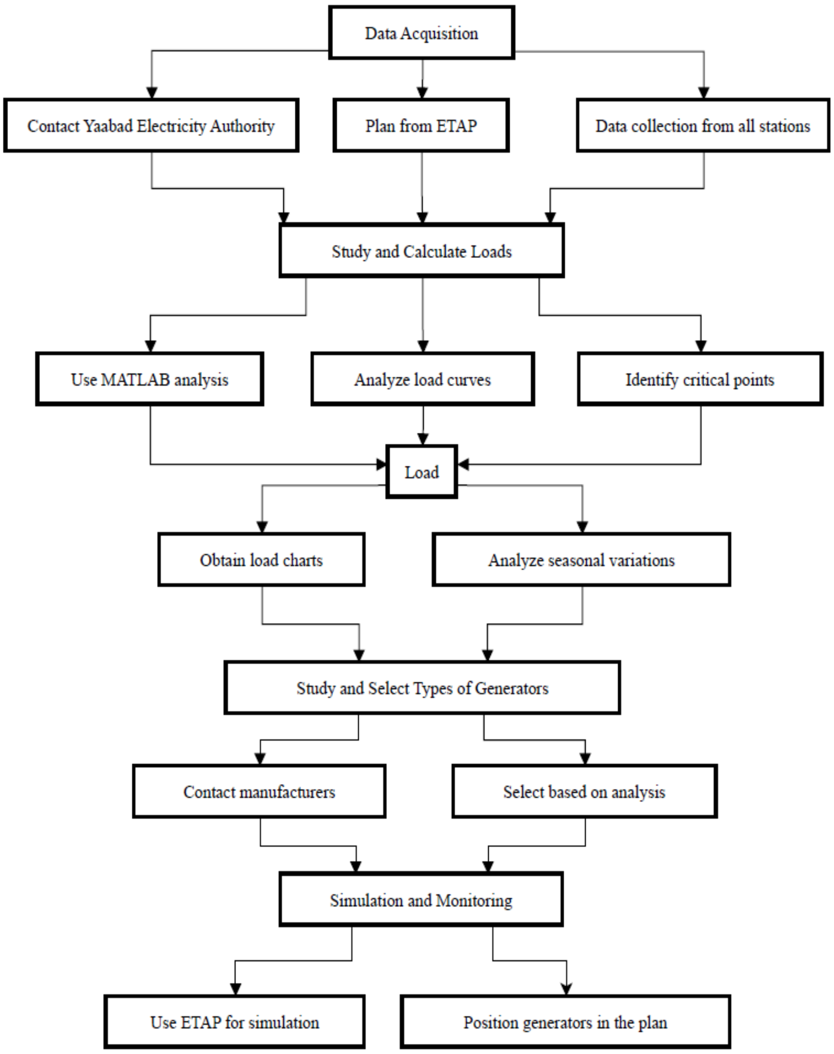


Figure 2: The main flow of the proposed analysis of Ya'bad energy system

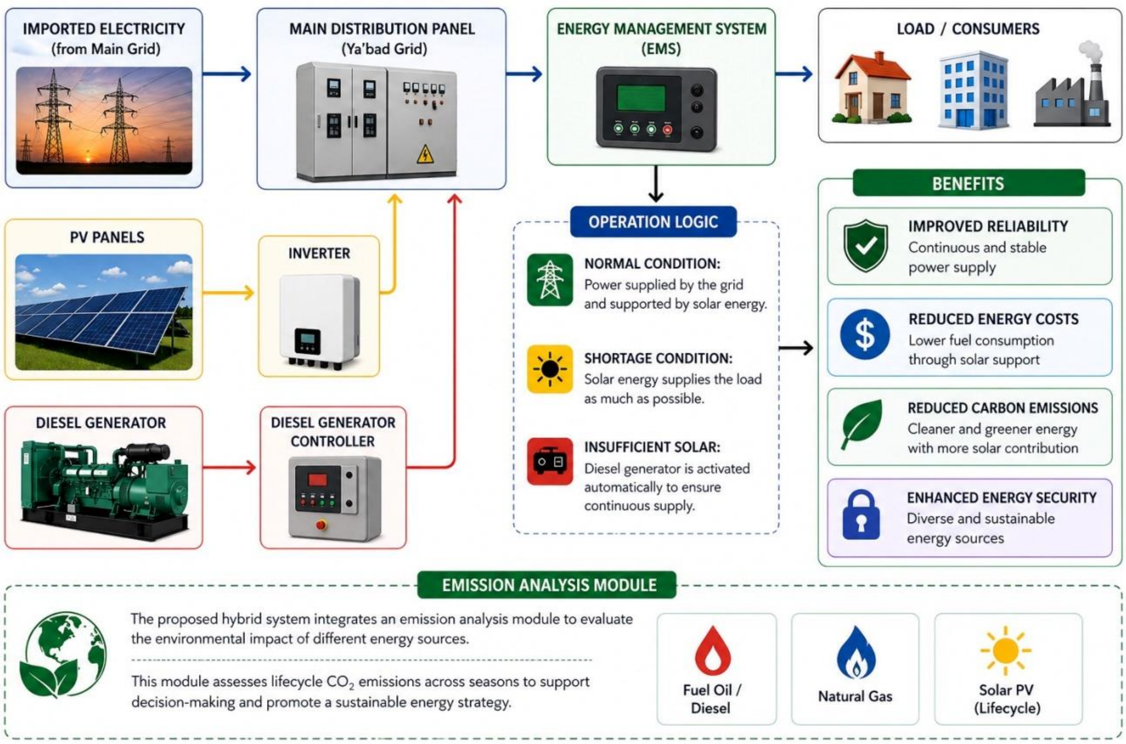


Figure 3: Hybrid PV–diesel energy system with EMS for reliable power supply in Ya’bad

compare the load consumption in each season. The plots provide a clear view of how the load varies by hour and by month, highlighting potential critical periods for generator operation, such as late evenings and colder months Implications for Diesel. This section includes all relevant graphs that visually represent the data and analysis results. The load curve for year 2023 is shown as in Figure 4.

Load analysis and energy modeling

A load curve is a plot showing the variation of load with respect to time. Load curve of a locality indicates cyclic variation, as human activity in general is cyclic. This results in load curve of a day does not vary much from the previous day load curves are useful for generation planning and enable station engineers to study the pattern of variation of demand. They help to select size & number of generating units and to create operating schedule of the power plant. Noting that the Average power is kWh consumed in the period / hours in the period, the Load factor is the ratio of average load to maximum demand which typically less than 1 which considered a measure of the effective use of the power station, and the Load Factor (LF) is expressed as average power / peak load.

Analyze the highest monthly power requirements, determine the maximum loads the system needs to handle and their seasonal variations. The times of peak load are primarily concentrated on specific dates and hours, particularly during the afternoon. Figure 5 shows the load curve for August 13, 2023, it shows how the total power demand varied throughout the day. The graph illustrates a peak in the mid-afternoon, consistent with our earlier findings of high load periods during warmer months. This peak specifically occurs around 16:00, which is one of the top peak loads.

Figure 6 shows the monthly peak loads, the minimum monthly peak load is about 7748.68 kW, whereas the maximum monthly peak load is 9764.77 kW, and the average monthly peak load is 8397.92 kW.

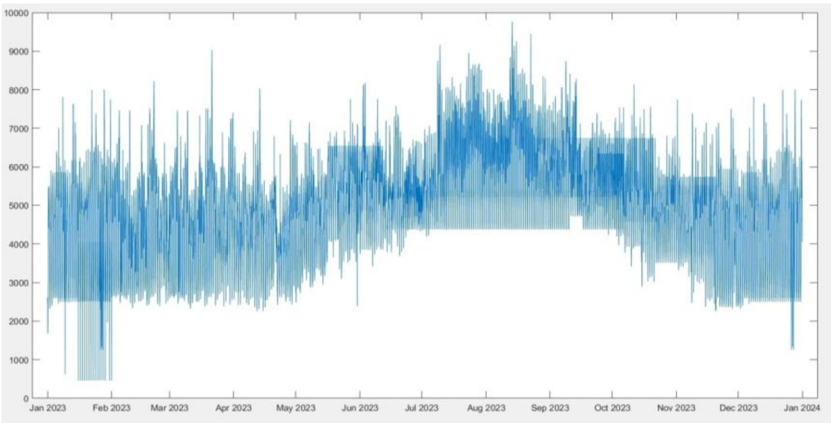


Figure 4: Load curve for the year 2023

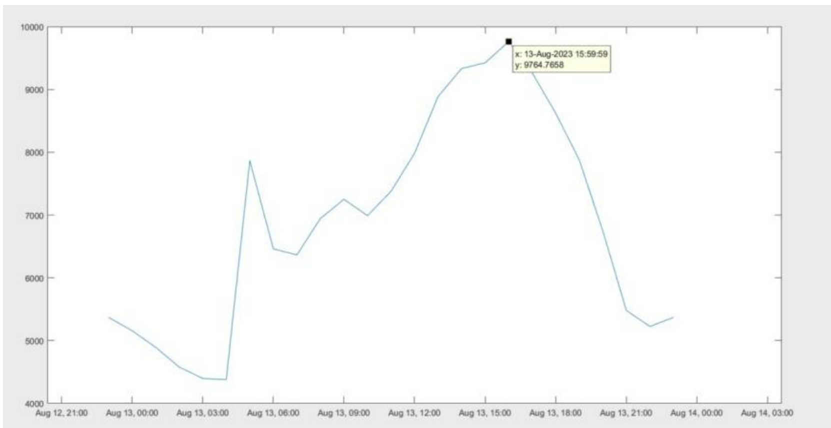


Figure 5: The Load curve for 13 august 2023

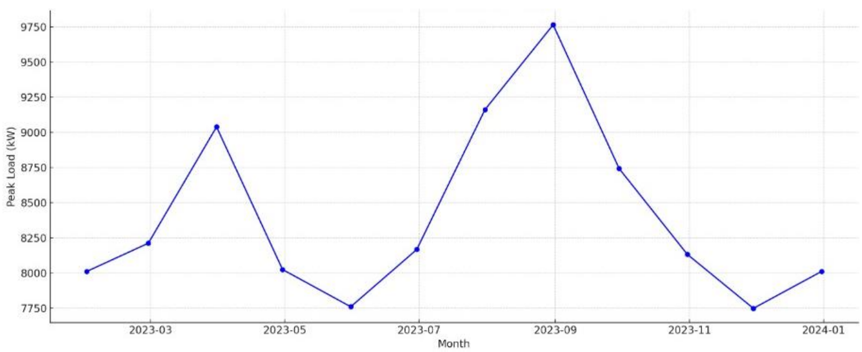


Figure 6: Monthly peak

The energy modeling of the PV system components depends on the equation [59, 90]:

$$E_{PV} = P_{STC}\left[1 + \beta_p (T_{cell} - T_{STC})\right] \frac{H_t}{H_{STC}}$$

Where: T_{STC} and T_{cell} are the PV cell's surface temperature at Standard Test Condition and under real operation conditions (°C), $\beta_p$is the power temperature coefficient (%/°C), and H_{STC} and H_t are the STC and real global solar irradiance incidents on the PV module surface. The equation for determining the surface temperature of the PV cell T_{cell} can be found using the following equation [23]:

$$T_{cell} = T_{\infty} + 7.8 \times 10^{-2} H_t$$

As illustrated, the required power fluctuates during different times of the day as well across months, with implications for generator operating scheduling. The average load varies significantly throughout the day, with the lowest consumption around 3654 kW and the highest around 6155 kW. Peak times typically occur in the evening (likely when solar production is low), and early morning hours show lower consumption. The load variation by hour of the day is illustrated in Figure 7.

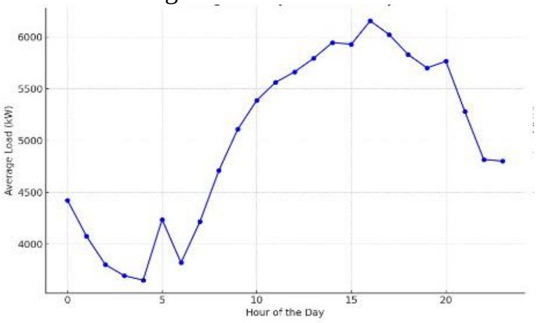


Figure 7: Load Variation by Hour of the Day

The monthly average loads also show variation, ranging from approximately 4303 kW to 6209 kW. Higher consumption is typically observed in winter and mid-summer, which may correlate with heating and cooling demands. The load variation by month is illustrated as in Figure 8.

Critical hours and the difference between the total energy consumed and the energy generated by solar cells is occurred at time of 16:00 at 13/08/2023. The load is 9764 kW, energy from PV is 1517 kWh, the difference between load and generated power is 8247 kWh as illustrated in Figure 9.

The following graphs clearly illustrate how the load changes hourly and monthly, highlighting potential critical periods for generator operation, such as late evening hours and colder months, which have implications for diesel consumption. Figure 10 illustrates the load curve for year 2023. Where Figures 11 illustrate the load curve for year seasons separately.

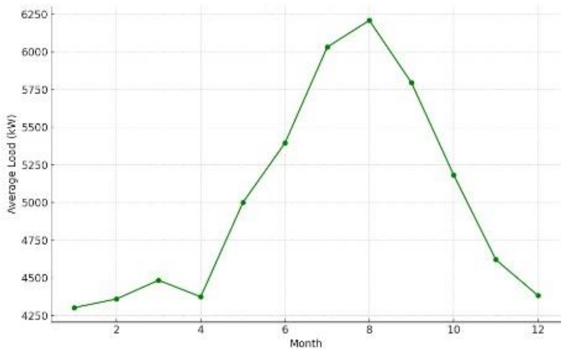


Figure 8: Load variation by month

$$average\ power = \frac{kwh\ consumed\ in\ the\ period}{hours\ in\ the\ period} = \frac{43947442}{8760} = 5016\ kWh$$

$$Peak\ load = 9765\ kW$$

$$load\ factor = \frac{average\ powar}{max.demand} = \frac{5016}{9765} = 0.514$$

Load curve for winter

$$average\ power = \frac{9448642}{2160} = 4374\ \text{kWh}$$

$$Peak\ load = 8212\ kW$$

$$load\ factor = \frac{4374}{8212} = 0.532$$

Load curve for spring

$$average\ power = \frac{10747100}{2208} = 4867\ \text{kWh}$$

$$Peak\ load = 9039\ kW$$

$$load\ factor = \frac{4867}{9039} = 0.538$$

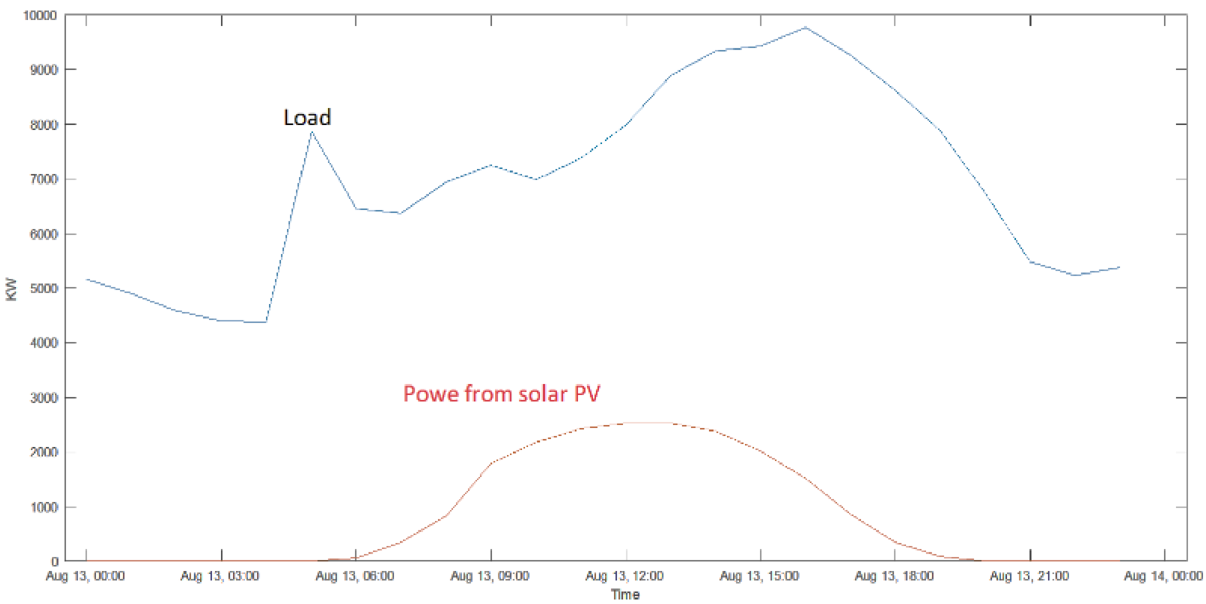


Figure 9: Critical hours and the total consumed and generated energy difference

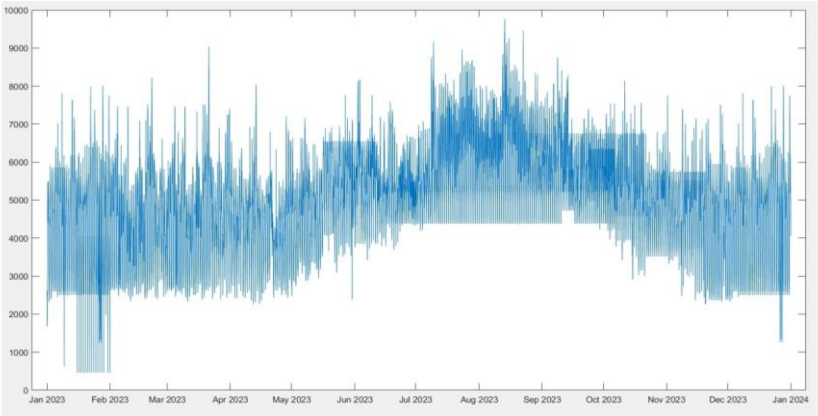
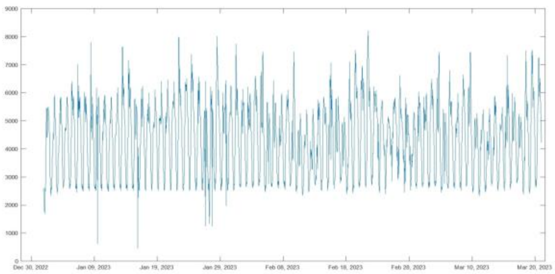
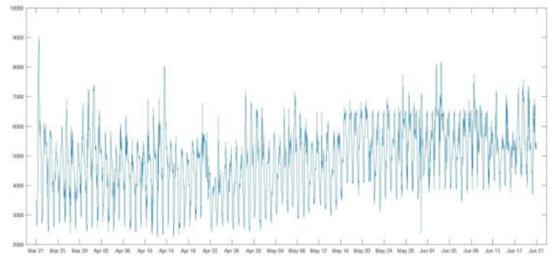


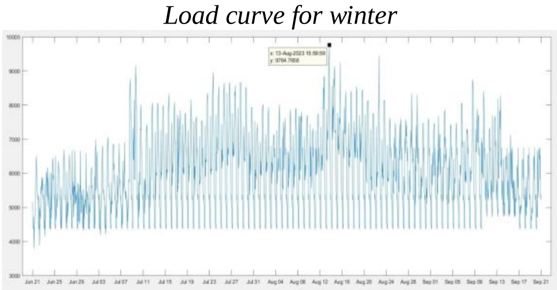
Figure 10: Load curve for year 2023



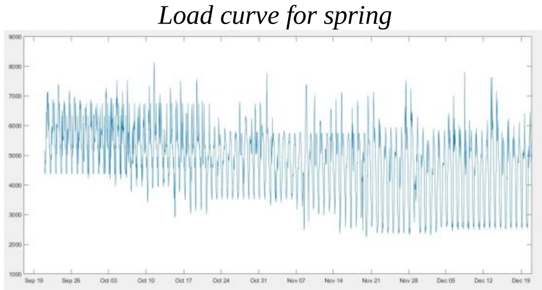
Load curve for winter



Load curve for spring



Load curve for summer



Load curve for Autumn

Figure 11: Load curve by seasons

Load curve for summer

$$average\ power = \frac{13181741}{2208} = 5969\ \text{kWh}$$

$$max.demand = 9765\ kW$$

$$load\ factor = \frac{5969}{9765} = 0.611$$

Load curve for Autumn

$$average\ power = \frac{10613280}{2184} = 4859\ \text{kWh}$$

$$max.demand = 8132\ kW$$

$$load\ factor = \frac{4859}{8132} = 0.597$$

Eco-environment analysis

A significant share of carbon dioxide emissions originates from conventional power plants that generate electricity by burning fuel oil/diesel or natural gas [91]. The combustion of fuel oil releases approximately 77 tons of CO_2 per terajoule (tCO_2/TJ), while natural gas emits about 55.8 tCO_2/TJ [92-94].

When converted to an electricity basis, these values are equivalent to approximately:

- Fuel oil/ diesel: 0.277 kg CO_2 per kWh of fuel energy (≈ 0.277 kg/kWh)
- Natural gas: 0.201 kg CO_2 per kWh of fuel energy (≈ 0.201 kg/kWh)

Based on these emission factors, this study analyzes two scenarios: power generation using fuel oil and power generation using natural gas, to assess the potential for reducing carbon dioxide (CO_2) emissions by replacing conventional fossil fuel-fired power plants with solar energy systems.

To provide a more comprehensive assessment of the proposed system, the economic evaluation was extended to include environmental externalities associated with CO_2 emissions [95, 96]. Incorporating the environmental damage cost improves the accuracy of the Levelized Cost of Energy (LCOE) and better reflects the true economic competitiveness of energy systems, particularly when comparing conventional and renewable technologies.

Accordingly, the LCOE is expressed as [91]:

$$LCOE = \frac{\left(\frac{r(1+r)^n}{(1+r)^n - 1}\right) \times C + C_{\text{O\&M}} - C_{\text{CO2}}}{E_{\text{t}}}$$

where r is the discount rate, n is the system lifetime (years), C is the initial capital cost ($), $C_{O\&M}$ represents the annual operation and maintenance cost ($), E_t is the total annual energy production (kWh), and C_{CO2} is the cost of environmental damage due to CO_2 emissions.

The economic feasibility is further evaluated using the Payback Time of Money (PBTM):

$$PBTM = \frac{C}{Income}$$

where Income represents the annual net revenue generated by the system.

The environmental cost associated with CO_2 emissions can be calculated by the following equation [97]:

$$C_{CO2} = EF_{CO2} \times E_t \times \emptyset_{CO2}$$

where EF_{CO2} represents the CO_2 emission factor of the electric power generation system (kg CO_2/kWh), $\emptyset_{CO2}$ represents the carbon social cost (\$/ton CO_2). In this study, the social cost of carbon is assumed to be 70 \$/ton CO_2, consistent with recent literature [96, 98].

By integrating C_{CO2} into the LCOE formulation, the proposed model accounts for environmental impacts alongside conventional economic parameters, enabling a more realistic and sustainable evaluation framework.

Results and Discussion

Required power from diesel generators

To determine the power required from diesel generators, the maximum demand recorded during critical hours subtracted from any power contributed by the solar panels during these times. Determining the peak load from the analysis, the highest load was recorded at 16:00 on 13 August 2023, with a demand of 9764.77 kW. Then subtract the solar contribution, assuming that the solar panels contribute 1517 kW at this time. Then the required power from diesel generator is 8247.77 kW. A diesel generator is needed with a capacity that is capable of supplying approximately 8247.77 kW to meet the power requirement during peak load time assuming that no other power source is available.

This section presented a detailed analysis and calculations necessary for the integration of diesel generators with existing solar power stations in the region of Ya'bad, Jenin. Key areas of focus include load analysis, peak load identification, and critical hour determination, which are crucial for specifying the correct configuration and number of diesel generators needed to ensure stable and efficient power supply.

Generator selection and balancing power

Generators can be categorized into several types based on their kinetic energy sources; the most common and widely used being diesel generators, water turbines, and wind turbines. Although water and wind are considered clean and renewable energy sources for electricity generation, the Ya'bad region lacks the necessary infrastructure for their use due to a shortage of dams and the limited availability of consistent, effective wind throughout the year. Consequently, diesel generators are preferred.

The appropriate generator to supply the loads is selected based on a study of load changes for at least one year in order to obtain load values that are close to accurate and simulate them with the real situation.

This study aimed to determine the average load value, as well as the lowest and highest load values and their durations. After performing calculations on load data between solar power plants and comparing them to the loads at the Israeli interconnection point of IEC, we arrived at the following results:

- There are 75 hours per year when the load from the IEC source is low, i.e., less than one megawatt. This is due to the ability of solar cells to cover a high percentage of the loads, and this period coincides with the peak hours of solar activity (mid-day).
- There are 5,947 hours per year during which the load from the IEC source is average, sometimes almost equal to the output of the solar panels. This value ranges between 1 and 5 megawatts, and this period includes the highest percentage of loads studied. This period falls during the late morning (before noon) and early evening (afternoon) hours.
- There are 2738 hours a year when the load is extremely high due to a lack of photovoltaic energy production during them, and this time represents the night and winter days.

Based on the above results derived from data collection and analysis of the supervisory SCADA program for load control of the Ya'bad Electricity Company, models were proposed to meet this demand, as shown in Table 2.

Table 2: GeneratorWP910-WP1125 Power Summary

	PRP(KVA)	PRP(KW)	ESP(KVA)	ESP(KW)
WP910	910.8	728.7	1000.1	800.1
WP1000	1023.5	818.8	1123.3	898.7
WP1125	1122.2	897.7	1247.5	998

Table 3: Fuel consumption (Liter / hour) for Generator WP910-WP1125

50 % load	**98**	**111**	**120**
75 % load	143	162	188
100 % load	195	215	244
110% load	218	240	269

Table 4: Generator WP1250-WP1350 Power Summary

	PRP (kVA)	PRP (kW)	ESP (kVA)	ESP (kW)
WP1250A	1250.1	1000.1	1345	1076
WP1250B	1252.8	1002.2	1381.7	1105.3
WP1350	1364.4	1091.5	1496.6	1197.3

Table 5: Generator WP1350-WP1750 Power Summary

	PRP (kVA)	PRP (kW)	ESP (kVA)	ESP (kW)
WP1350A	1363.3	1090.6	1496.7	1197.3
WP1500B	1510.9	1208.7	1660	1328
WP1750	1728	1382.4	1873	1498.4

Table 6: Fuel consumption (Liter / hour) for Generator WP1250-WP1350

50% load	**144.6**	**144.6**	**152.7**
75% load	201.1	201.1	215.9
100% load	263.1	263.1	286.6
110% load	292.2	292.2	322.4

Table 7: Fuel consumption (Liter / hour) for Generator WP1350-WP1750

50% load	**154.2**	**156.8**	**178.2**
75% load	212.8	226.4	262.2
100% load	281	297.5	353
110% load	308.2	329	TBC

Table 8: The relationship between loads and diesel generators

Generator 1	**When load < 1.125 MW**
Generators 1+2	1.125 MW < load < 2.875 MW
Generators 1+2+3	2.875MW < load < 4.225 MW
Generators 1+2+3+4	4.225MW < load < 5.350 MW
Generators 1+2+3+4+5	5.350MW < load < 6.700 MW
Generators 1+2+3+4+5+6	6.700 MW < load < 8.450 MW
Generators 1+2+3+4+5+6+7	8.450 MW < load < 9.575 MW

After analyzing the electrical loads on the grid, the difference in the value of the loads taken from the source was noted, and generators with appropriate capacities were selected, and the difference in fuel consumption for each generator was noted based on the generator's capacity and the load ratio on each one.

After a power outage, the control unit senses the interruption of power supply and sends a signal to the generators to start and supply the loads. During the load-generating process, the control unit monitors the load on the generators and instructs the fuel pump to adjust the fuel quantity, either decreasing or increasing it accordingly. This adjusts the generator speed and frequency, and consequently the voltage, to meet the load requirements.

The same principle applies to generator operation sequences. The control unit senses the load on the generators, and if the load exceeds a generator's capacity, it signals the next generator to start. For example, when the first generator is operating at a load of approximately 1.125MW and the load increases, a signal is sent to the second generator to start and begin loading. When the mains power returns, a signal is sent to the generators indicating the return of power. They then wait briefly to ensure the current in the network is stable. Once this is confirmed, the generators are switched off, and the load is returned to the mains.

System simulation modeling and load flow analysis

This section presents a simulation of a hybrid electrical grid incorporating solar cells and diesel generators, along with a load flow analysis of the system. The methodology for simulating transient load flow using ETAPs software is explained, and the hybrid system design and analysis are detailed, as is the integration of diesel generators with solar cells into the grid. Figure 12 shows the creation of the structural model of the city of Ya'bad on the ETAP program, where all the city's loads were connected in addition to the solar power stations that were previously connected.

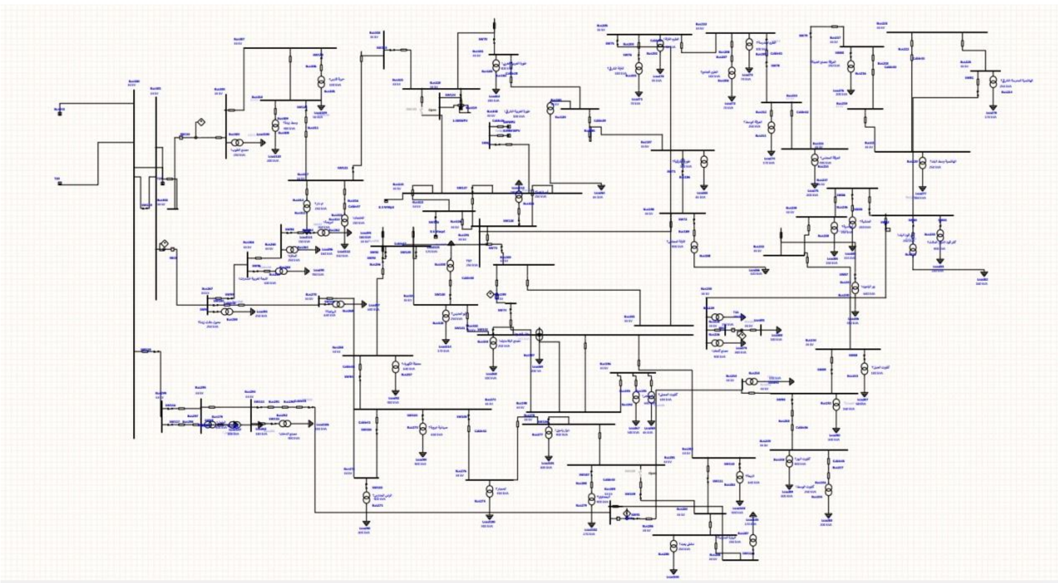


Figure 12: Ya'bad Grid

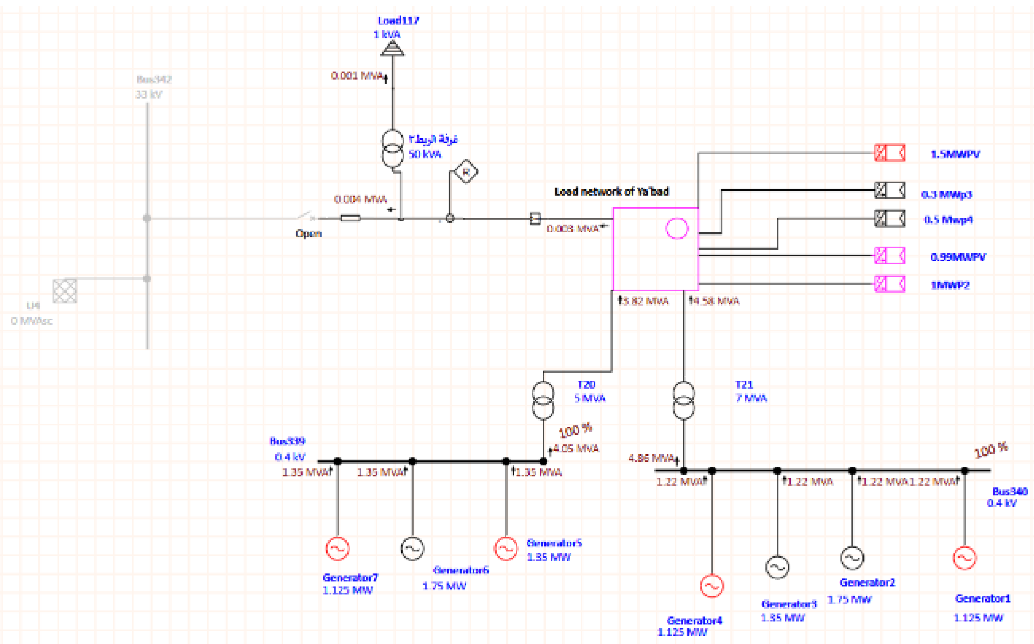


Figure 13: Generator modeling

This section, have identified the optimal locations for installing electrical generators in the town and distributing them in a way that ensures balance of loads and effective distribution of electricity. Figure 13 shows the electrical load network was added in a block representing these loads, and the solar power generation stations were connected to the block.

Figure 14 shows the five previously connected solar power plants with different generating capacities, with a total of 4.3 megawatts, operating at maximum generating capacity.

Load flow analysis

The load flow analysis is a numerical analysis of the flow of electrical energy in any electrical system. The load flow study is considered an assessment of the steady-state conditions of the electrical system. Its goal is to determine the flow of power, current, voltage, real power, and reactive power in the system. This study evaluates the system's ability to provide loads appropriately while remaining within the required voltage and current ranges. The load flow study report will determine the electrical voltage. The power factor across all buses in addition to the current flow through all feeders.

Figure 15 shows the preparation of the analysis of the Ya'bad electricity network after performing a load flow analysis.

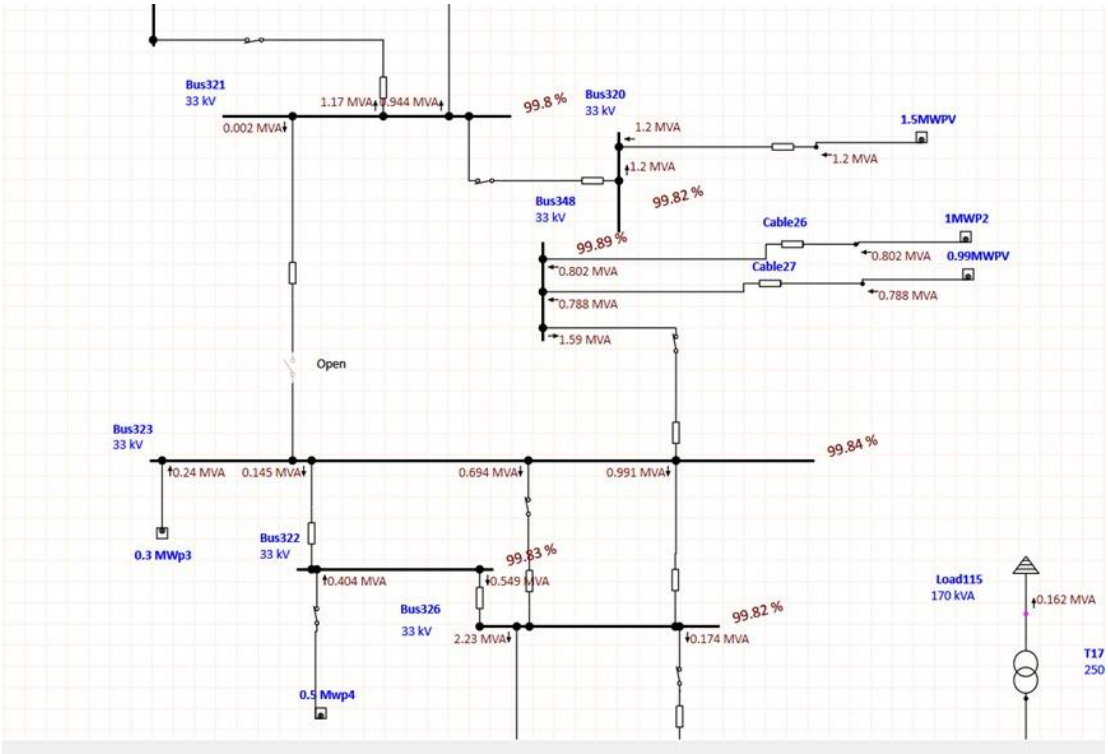


Figure 14: Solar cell stations located and connected to the grid

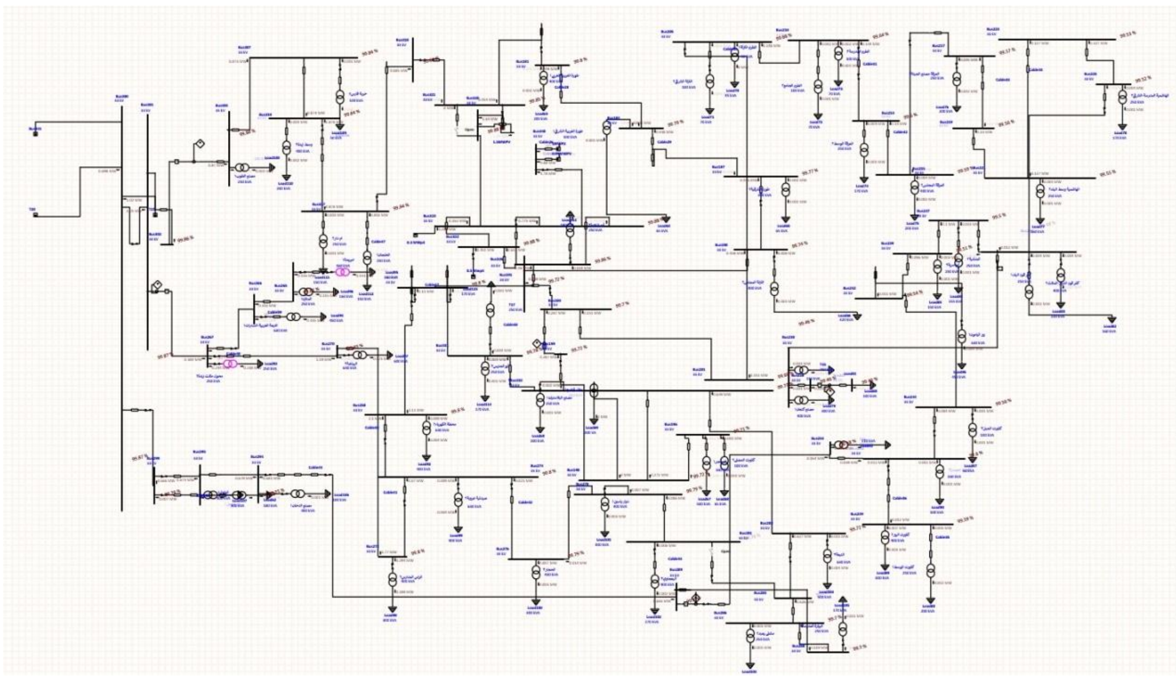


Figure 15: load flow analysis

Load flow report and result Using Newton-Raphson method

Table 9 shows the results of the load flow on the network, it shows that there is no drop in voltages. This indicates that the generators integrated with the solar cells give full power without errors on the network or drop in voltage. This represents the power generation share on the grid. The role of modeling and simulation in system transformation processes highlights the use of the Newton-Raphson method to study load flow and the simulation process to ensure the integration of diesel generators on the grid [99].

Table 9: Load flow report and result

Bus ID	Nominal KV	Voltage pu	MW Loading	Mvar Loading	Amp Loading
Bus170	33	99.94	0.896	0	15.68
Bus171	33	99.95	0.88	0	15.41
Bus181	33	99.8	0.453	0.78	15.82
Bus184	33	99.79	0.449	0.606	13.23
Bus187	33	99.77	0.448	0.551	12.46
Bus190	33	99.74	0.446	0.492	11.65
Bus191	33	99.72	0.438	0.19	8.378
Bus196	33	99.71	0.014	0.54	9.482
Bus198	33	99.72	0.287	1.411	25.26
Bus199	33	99.72	0.287	0.875	16.16
Bus200	33	99.7	0.438	1.073	20.34
Bus201	33	99.68	0.151	1.076	19.06
Bus205	33	99.68	0.151	1.076	19.06
Bus210	33	99.64	0.147	1.03	18.28
Bus213	33	99.6	0.144	1.084	19.21
Bus215	33	99.59	0.14	0.96	17.04
Bus217	33	99.57	0.136	0.768	13.7
Bus219	33	99.56	0.13	0.607	10.91
Bus221	33	99.55	0.13	0.609	10.94
Bus223	33	99.53	0.127	0.487	8.84
Bus225	33	99.52	0.127	0.489	8.875
Bus227	33	99.46	0.0009	0.0989	1.74
Bus228	33	99.46	0.0009	0.0948	1.668
Bus230	33	99.46	0.0114	0.529	9.315
Bus234	33	99.48	0.123	0.888	15.77
Bus237	33	99.5	0.103	0.696	12.37
Bus239	33	99.51	0.0995	0.837	14.82
Bus242	33	99.54	0.0961	1.268	22.35
Bus244	33	99.56	0.0851	1.324	23.31
Bus249	33	99.59	0.0124	0.463	8.136
Bus252	33	99.6	0.0831	1.865	32.79
Bus254	33	99.68	0.0669	1.967	34.55
Bus258	33	99.8	2.108	2.653	59.41
Bus265	33	99.87	0.313	0.0048	5.488
Bus266	33	99.87	0.755	0.0139	13.22
Bus267	33	99.87	1.182	3.834	70.28
Bus270	33	99.83	1.771	3.824	73.86
Bus272	33	99.8	2.068	3.806	75.93
Bus274	33	99.8	2.099	3.813	76.31
Bus276	33	99.79	0.021	0.819	14.37

Bus278	33	99.79	0.0136	0.53	9.295
Bus281	33	99.78	0.0062	0.24	4.204
Bus283	33	99.72	0.639	0.484	14.07
Bus284	33	99.71	0.626	0.161	11.35
Bus286	33	99.7	0.626	0.305	12.23
Bus288	33	99.7	0.623	0.469	13.69
Bus289	33	99.7	0.683	2.434	44.36
Bus294	33	99.75	0.681	2.49	45.27
Bus295	33	99.77	0.678	2.662	48.18
Bus299	33	99.79	0.673	2.921	52.56
Bus300	33	99.87	1.714	8.092	144.9
Bus301	33	99.87	1.052	5.172	92.46
Bus302	33	99.86	0.869	1.342	28.01
Bus304	33	99.84	0.872	1.349	28.15
Bus307	33	99.84	0.874	1.253	26.77
Bus310	33	99.84	0.878	1.207	26.15
Bus317	33	99.84	0.885	1.037	23.9
Bus318	33	99.84	0.885	0.767	20.53
Bus319	33	99.88	1.34	0	23.47
Bus320	33	99.88	1.34	0.0004	23.47
Bus321	33	99.85	1.34	0.776	27.12
Bus322	33	99.88	0.613	0.0055	10.74
Bus323	33	99.88	2.043	0.0244	35.79
Bus326	33	99.86	2.494	0.174	43.8
Bus327	33	99.8	2.488	2.279	59.15
Bus331	33	99.78	0.377	2.146	38.21
Bus332	33	99.73	0.641	1.827	33.97
Bus339	0.4	100	0.672	3.922	5743
Bus340	0.4	100	0.994	4.665	6885
Bus348	33	99.94	1.776	0.0212	31.1

Annual CO_2 Emission Reductions

Table 10 presents the seasonal and annual reductions in CO_2 emissions achieved when solar energy is used instead of conventional electricity generation based on fuel oil/diesel and natural gas. The results clearly demonstrate that replacing fossil-fuel-based generators with solar energy leads to substantial emission mitigation across all seasons.

Seasonally, the highest emission reductions are observed during the summer period, with avoided emissions reaching approximately 3,651 tCO_2 for fuel oil/diesel and 2,650 tCO_2 for natural gas. This is directly linked to the higher electricity demand recorded in summer, which increases the baseline fossil-fuel emissions and, consequently, the potential reduction when solar energy is implemented. Conversely, winter shows the lowest reduction values (about 2,617 tCO_2 for diesel and 1,899 tCO_2 for natural gas), reflecting the lower seasonal energy consumption.

On an annual basis, the total avoided emissions amount to approximately 12,185 tCO_2 when replacing fuel oil/diesel generators and 8,842 tCO_2 when replacing natural gas generators. These figures indicate that solar energy can eliminate a significant portion of greenhouse gas emissions associated with conventional power generation. Furthermore, the higher reduction values observed in the diesel case confirm that diesel-based electricity generation has a greater carbon intensity compared to natural gas, making the environmental benefit of switching to solar even more pronounced.

Table 10: Seasonal reductions in CO_2 emissions when using PV instead of fuel-powered generators

Seasons	Fuel oil/Diesel (tCO_2)	Natural gas (tCO_2)
Winter	2617.27	1899.18
Spring	2976.95	2160.17
Summer	3651.34	2649.53
Autumn	2939.88	2133.27
Annual	12185.44	8842.15

Life-cycle CO_2 Emissions Associated with PV Systems

Although photovoltaic (PV) systems generate electricity without any direct emissions during operation, they are not entirely emission-free when evaluated over their full lifecycle. Carbon dioxide (CO_2) emissions associated with

PV systems primarily arise from upstream processes, including the extraction and purification of raw materials (such as silicon), manufacturing of solar cells and modules, production of aluminum frames and glass components, transportation of equipment, and installation activities. Additional minor emissions may occur during maintenance and at the end-of-life stage through dismantling and recycling processes. These lifecycle emissions are typically quantified through Life Cycle Assessment (LCA) methodologies and are significantly lower than those of fossil-fuel-based power generation. On average, PV systems emit approximately 30–50 gCO_2 per kWh over their lifetime, compared to several hundred grams per kWh for conventional diesel or natural gas plants. Therefore, while PV technology is not entirely carbon-neutral in absolute terms, its overall carbon footprint remains minimal and substantially lower than that of traditional fossil-fuel energy sources.

Figure 16 illustrates the seasonal variation of CO_2 emissions associated with electricity generation using fuel oil/diesel, natural gas, and solar photovoltaic (PV) systems based on lifecycle emissions. As expected, emissions from all energy sources follow the same seasonal trend as electricity demand, with the highest values recorded in summer and the lowest in winter. However, a substantial difference is observed in the magnitude of emissions among the three technologies. Fuel oil/diesel exhibits the highest CO_2 emissions across all seasons, followed by natural gas, while solar PV demonstrates significantly lower emission levels. For instance, during the summer peak, emissions from diesel generation exceed 3,600 tCO_2, compared to approximately 2,650 tCO_2 for natural gas and less than 600 tCO_2 for PV systems. This represents an emission reduction of approximately 85–90% when replacing diesel with PV, and about 75–80% when replacing natural gas with PV. The pronounced gap between the PV curve and fossil-fuel curves highlights the strong decarbonization potential of solar energy. Since PV systems produce no direct operational emissions and only minor lifecycle emissions related to manufacturing and installation, their integration into the electricity supply mix offers a highly effective strategy for achieving significant reductions in greenhouse gas emissions and supporting long-term climate mitigation objectives.

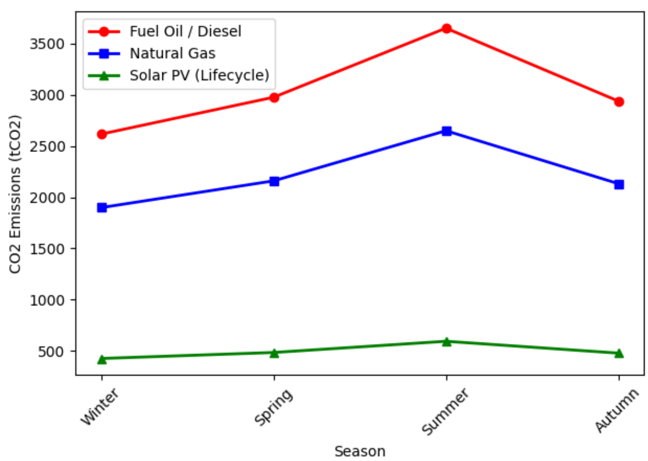


Figure 16: Seasonal variation of CO_2 emissions associated with electricity generation using fuel oil/diesel, natural gas, and solar photovoltaic (PV) systems based on lifecycle emissions

Conclusion

This paper demonstrated the successful integration of diesel and solar energy systems in the city of Ya'bad Jenin. A key finding is the improved grid reliability achieved through the hybrid system, which provides a stable power supply, particularly during periods of high sunshine. The system is also capable of handling peak loads using diesel generators to meet peak demand requirements of 8247.77 kW. Furthermore, the system is characterized by stability as it was designed to remain stable without significant voltage drops or interruptions, and the system has demonstrated the ability to stabilize voltage across all buses at rates of (99.46% – 100%). Hybrid systems offer both economic and environmental benefits. Cost savings and environmental advantages were achieved by reducing fuel consumption and carbon dioxide emissions by 12,185 tons of CO_2. These findings recommend that policymakers support sustainable energy projects in line with raising awareness of the benefits of renewable energy. Future efforts should focus on scaling up hybrid systems to encompass multiple areas or different types of communities.

Author Contributions: Conceptualization: Anees Abu Sneineh, Mohamed Elnaggar, Hala J. El-Khozondar and Mohammed J.K. Bashir. Methodology: Anees Abu Sneineh, Wael A. Salah, Hala J. El-Khozondar and Yasser F. Nassar. Software: Validation: Mohamed Elnaggar, Anees Abu Sneineh and Mai Abuhelwa. Formal analysis: Mohamed Elnaggar and Wael A. Salah. Investigation:. Data curation: Mohamed Elnaggar and Alfian Ma'arif. Writing—original draft preparation: Wael A. Salah, Anees Abu Sneineh, Mohamed Elnaggar, Hala J. El-Khozondar. Writing—review and editing: Wael A. Salah, Anees Abu Sneineh, Mohammed J.K. Bashir, and Mai Abuhelwa Visualization: Yasser F. Nassar, Alfian Ma'arif. Supervision: Mohamed Elnaggar and Mohammed J.K. Bashir.

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