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Towards Energy Sustainability in University Campuses: A Case Study of Beirut Arab University

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Abstract: Lebanon has been suffering from severe challenges in its electric sector for decades owing to chronic supply shortages and faults in its aging power grid infrastructure. The deplorable situation of the Lebanese electric sector has been made worse by the economic meltdown that started in 2019, which eventually led to total power blackouts across the country. In this paper, we present a case study on the design and implementation of a solar microgrid system for Beirut Arab University, Lebanon. As a first step, simulation software for a microgrid and a distributed generation power system is used to compare different design scenarios. Considering the available installation area and the fact that the greatest demand occurs during the daytime, when both the educational and managerial facilities are running, it is found that a 500-kW photovoltaic system tied to the university's already present diesel generators is the optimal solution in terms of return on investment. The second step details the actual implementation of the system in the Beirut campus and the evaluation of the system's performance in terms of diesel cost savings and emissions reduction. We expect that the results of this case study will encourage other institutions and communities to adopt sustainable and renewable energy sources.

Keywords: sustainability; renewable energy; photovoltaic system; case study; green campus; HOMER simulation

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1. Introduction

The availability of electricity has emerged as a fundamental necessity in today's world and is widely recognized as a key catalyst for driving progress, spurring economic growth, and mitigating poverty [1–3]. It plays an indispensable role in enabling us to carry out our daily routines with ease while also serving as an essential component of human rights [4]. Despite its undeniable importance, the challenge of generating adequate electricity continues to persist. The global community finds itself grappling with critical shortages exacerbated by various factors such as international disputes and soaring fuel prices caused by inflation. These obstacles have made it increasingly challenging for nations worldwide to meet their energy demands efficiently. For instance, Nigeria, the largest economy on the African continent, has struggled with its power sector due to its rapidly growing population [5]. Even developed nations are taking steps to regulate their energy consumption and manage rising energy prices [6]. Another important aspect of power generation from rapidly depleting nonrenewable resources is pollution and its harmful effects [7]. The production of electricity affects the environment significantly; thermal plants emit hazardous chemicals into the atmosphere, while nuclear plants produce even more dangerous waste. Moreover, both transmission and distribution systems leave undeniable visual impacts on their surroundings [8].

Our planet receives an immense amount of solar radiation and wind movement from the sun [9]. To address the decline in global electrical sectors and to satisfy the demand for sustainable, environmentally friendly energy sources, nations have turned to renewable energy options as a substitute for thermal power methods that rely on fossil fuels [10]. Renewable energy sources, including wind and solar, produced a total of 915 GW worldwide in 2018, as per [11], with an increasing trend expected for the coming years. Figure 1 shows the global energy production of various energy sources from 1965 to 2021 [12]. Predictions suggest that by 2030, renewable energy could make up 65% of global energy production and reach nearly zero net emissions by achieving a share of up to 90% by 2050 [13,14]. This proves that sustainable energy solutions have become an integral part of modern society. Different sectors across the world are taking steps towards becoming more environmentally friendly and reducing their carbon footprint. In this regard, sustainability on campus has become a crucial aspect that needs to be addressed to reduce the negative impacts of electricity generation on the environment and to reduce energy costs.

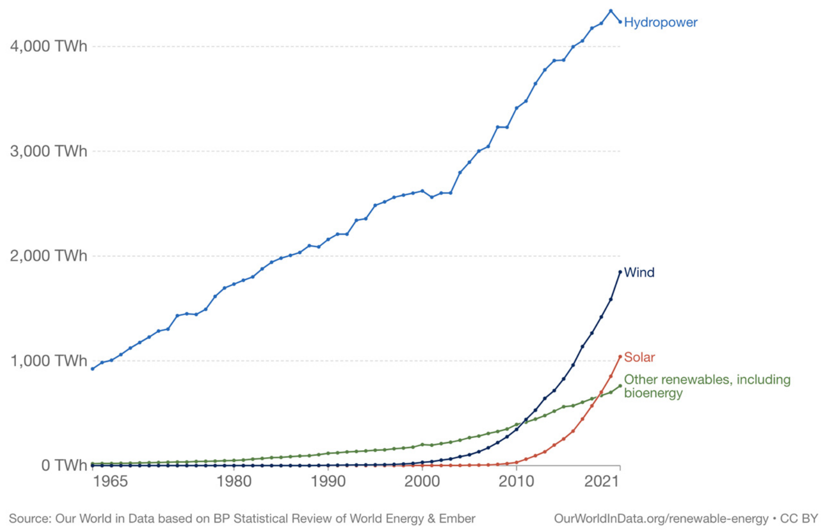


Figure 1. The global growth of renewable energy generation.

Lebanon, a tiny nation on the eastern edge of the Mediterranean Sea, has long grappled with recurring blackouts and an immense electricity deficit [15] that amounts to 40% of its national debt. This scarcity was exacerbated by the economic turmoil that began in Lebanon in 2019, which resulted in currency inflation reaching as high as 8580%, where USD 1 equaled LBP 1515 at the start of that year but rose to a staggering figure of LBP 130,000 LL early 2023. In addition to this existing shortfall, more challenges were added, such as Beirut's port explosion during August 2020, damaging an enormous area encompassing Electricité Du Liban (EDL), which is responsible for almost all Lebanese power production. Furthermore, there is the current worldwide fuel crisis contributing collectively toward creating one of history's worst energy crises. The entire country entered a complete blackout for days and months, and in best cases, power was provided for 4 h each day. Yet, Lebanon is blessed with abundant sunlight, wind, and water. The variety and availability of renewable energy sources in a country such as Lebanon make them an optimal choice to supplement electricity generation. Indeed, Lebanon enjoys a mild Mediterranean climate offering 7 months (from April to October) of dry season per year [16], which makes it perfect for one of the most popular forms of renewable energy, namely solar energy. This was proved by the vast increase in the amount of installed solar systems all over Lebanon, which reached a maximum of 89.84 MWp of solar power with a cumulative investment of USD 135.19 million by 2020, with USD 11.11 million invested in 2020 alone [17].

Beirut Arab University (BAU) is an institution that requires a significant amount of electrical energy to run its facilities. As an institution that focuses more on the practical part of education, the demand for electrical power is higher. Therefore, electricity is a must that should be put at the top of its priorities. An institution of this size under these circumstances is comparable to the small island mentioned in [18], where solar energy was considered to be the optimal solution for electricity generation. Additionally, similar case studies using HOMER were presented in [19]. An on-grid solar power system coupled with the already present diesel generators can reduce fuel costs and completely cover the daily demand for electric power. Moreover, isolating BAU into a semi-independent microgrid has its advantages, such as enhancing power quality, system stability, and voltage and frequency regulation.

This paper discusses, in detail, the on-grid solar system that BAU, as a microgrid, installed to secure its energy demands. Several scenarios are first studied to show that the on-grid system is the most efficient and economical solution. The system is then checked using HOMER software to validate the grid-tied solution. The rest of this paper is divided into the following sections. Section 2 gives the problem statement and the system design. In Section 3, HOMER simulations are performed to check the system design. Section 4 presents the implementation of the selected system, and finally, Section 5 draws the conclusions of this study.

2. System Design

As an educational institution, BAU requires a significant amount of energy to operate, making it a microgrid by itself. Normally, five low-voltage (380 V, 50 Hz) generators are used to cover the demand of the Beirut campus, which is 1700 kVA, but with soaring fuel prices, this solution is no longer considered economically feasible. Given the limited availability of utility power supply, these generators operate in a primary mode and establish a microgrid, which will henceforth be referred to as the grid. In other words, the grid in on-grid and off-grid terms refers to the microgrid formed by the diesel generators. On the other hand, for an institution such as BAU, reducing supply is not an option. Lebanon has many sunny days per year, and the same naturally goes for BAU. Here, solar energy is a practical solution to this problem. Based on this, three scenarios are considered, studied, and compared, and the most feasible solution is chosen. The first scenario is the strategy that was originally used, where diesel generators supply the load without any additional energy sources. In the second scenario, no generators are used, and the solar panels, together with a battery storage system, supply the load alone, making it an off-grid system. The third and final scenario to be discussed is an on-grid system in which the solar system is installed in conjunction with generators to feed the load.

2.1. Diesel Generators System

Thermal energy generation is one of the oldest ways to generate electricity. It is still the most common method of generating energy worldwide. Diesel generators are an example of this type and are currently the main suppliers of electric power in Lebanon, where electricity from the grid is practically absent. In BAU, five diesel generators are already present with a total capacity of 4500 kVA, satisfying the 2N + 1 redundancy method, which supplies the full load of the university but comes with the huge cost of both the fuel that keeps it running as well as the price of oil and filters for the generators. The generators, without the presence of any other energy sources, consume approximately 60,000 L of diesel per month in the study semesters, which is equivalent to USD 57,660. This is in addition to approximately USD 500 for oil, filter changes, and maintenance. This adds up to USD 58,110 per month, which is clearly too expensive to pay only for electricity. In addition, in Beirut, a big city where trees are rare, the emissions from these generators and the pollution they cause can never be taken lightly. Hence, things cannot continue as they are, and if no action is taken, serious health and economic consequences will be inevitable. Table 1 lists the advantages and disadvantages of the proposed method.

Table 1. Advantages and disadvantages of using only diesel generators.

Advantages	Disadvantages
Low initial cost	High operation cost
Existing	High fuel cost
No need for additional networks	High emissions
Reliable	Severe effects on environment and health

2.2. Off-Grid System

Another appealing solution to the electricity problem is an off-grid solar system. In this system, solar panels are used to feed the microgrid and charge the batteries whenever the sun is present; when sunlight is absent, the batteries are responsible for feeding the load. Therefore, there is no need for diesel generators, and they can be disconnected. Such systems are becoming more popular all over Lebanon and have proved to work well on a domestic scale. In this study, the number of batteries considered can feed the normal load of the university on a study day for eight continuous hours without other energy sources. The load considered is approximated to 1700 kW for 8 h; thus, 13,600 kWh of energy storage will be required. Lithium-ion batteries will be considered for this study owing to their advantages over other battery types. Hence, a 15 kWh LiFePO4 battery, with a unit price of around USD 2200 as per the Felicity brand in November 2022, will be considered. To supply the load for the required duration, 907 of these batteries will be needed. As a result, the cost of the batteries alone will be USD 1,995,000. In addition, to both feed the load and charge the batteries, more panels are required. The number of panels required was calculated to be 3000 panels. Each panel has an area of 2 m^2, and the total area needed is 6000 m^2, which far exceeds the available area of 2000 m^2. With 3000 panels, the cost of the system without batteries will be USD 3,100,000, so the overall cost of the project will sum up to USD 5,095,000. Therefore, this scenario presents great difficulties in terms of both economic and physical aspects, making it difficult to achieve. Table 2 presents the advantages and disadvantages of this scenario.

Table 2. Advantages and disadvantages of the off-grid system.

Advantages	Disadvantages
Complete independence	High investment cost
No fuel costs	Low reliability
Environmentally friendly	Large numbers of panels required
Sustainable	Needs a lot of space

2.3. On-Grid System

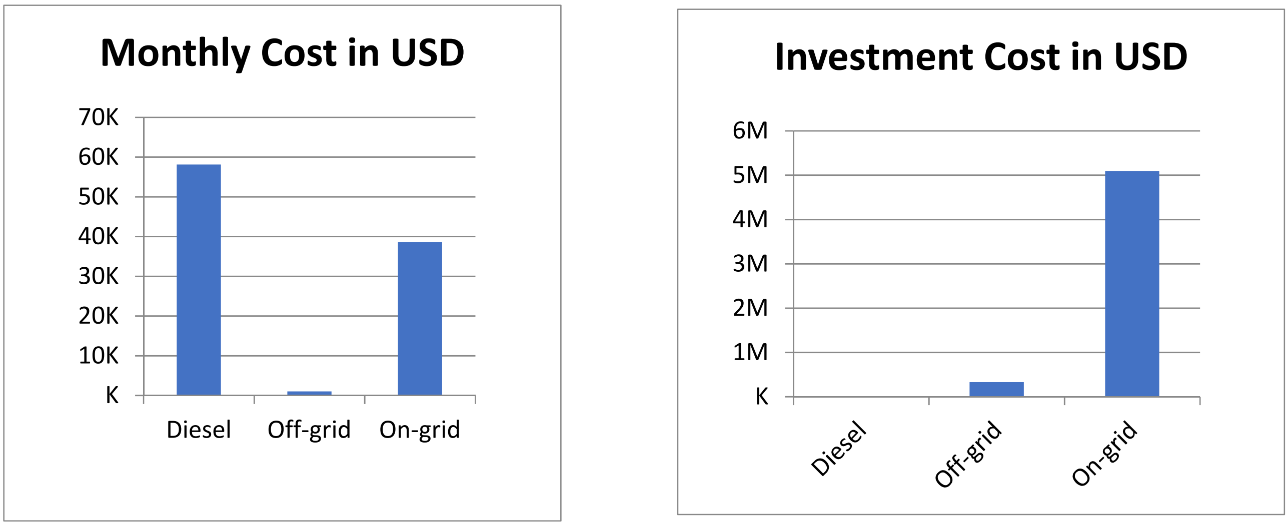
In this system, the solar system is coupled with generators to supply the load. Such systems are especially popular in advanced countries with proper grid supply but are inapplicable in cases where the grid supply is unstable or, in Lebanon's case, absent. However, BAU possesses diesel generators large enough to make a micro-grid system; in this case, an on-grid system composed of a solar power system aided by the diesel generators becomes possible. Compared to the off-grid system, the on-grid system requires less solar generation capacity, which significantly reduces the investment cost. At the same time, the stress on the diesel generators significantly decreases, thus cutting down on both fuel and maintenance costs. The on-grid system requires 960,550 W solar panels and a number of on-grid inverters, amounting to USD 330,000, which is more logical than the high monthly cost of the diesel generators and the prohibitive investment cost of the off-grid system. In addition, 960 panels with an area of 2 m^2 per panel will occupy 1920 m^2, which is compatible with the available area of 2000 m^2. Table 3 presents the advantages and disadvantages of the proposed scenario. Additionally, BAU is a full-time higher educational institution that requires power for critical equipment, especially in laboratories; hence, the reliability of the power supply is necessary, which is also achieved in this system owing to the existence of diesel generators in the event of extended cloudy periods.

Table 3. Advantages and disadvantages of the on-grid system.

Advantages	Disadvantages
Lower investment cost	Dependent on generators
Lower fuel cost	Moderate pollution
Less maintenance	
Compatible with the available space	
Reliable	
Sustainable	

2.4. Feasiblity Study

BAU's main facilities usually operate for 176 h per month, and for every 100 kVA, a generator uses about 20 L of diesel per hour. For a main load of 1700 kVA, the amount of diesel needed is equal to 60,000 L per month, costing approximately USD 57,610 and increasing to USD 58,110 per month after adding the maintenance costs. It is possible now to determine the payback period of the off-grid system. For an overall cost of USD 5,095,000, knowing that the university spends USD 58,110 USD per month and that each study semester consists of four months, we conclude that the project has a payback period of 22 semesters or 11 years, which is too long based on the evaluation methods used in [20], especially considering that the batteries are to be replaced every 7 to 8 years. For the on-grid system, installing a 550 kW solar system decreases the load on the generators to 1150 kVA, hence consuming 230 L/hour or 40,000 L/month and decreasing the monthly fuel cost to USD 38,407. In addition, the maintenance cost decreases to half of the original owing to decreased stress and fewer operation hours, hence making the monthly cost USD 38,657, which shows a significant decrease of USD 19,453 against the original costs for a relatively low capital investment. As for the payback period of this system, where capital investment is USD 330,000, it is calculated to be four semesters, so this project returns its value in less than two years, which is a relatively short period for such a project. Figure 2 shows bar graphs for the monthly costs and investment costs of the different systems.

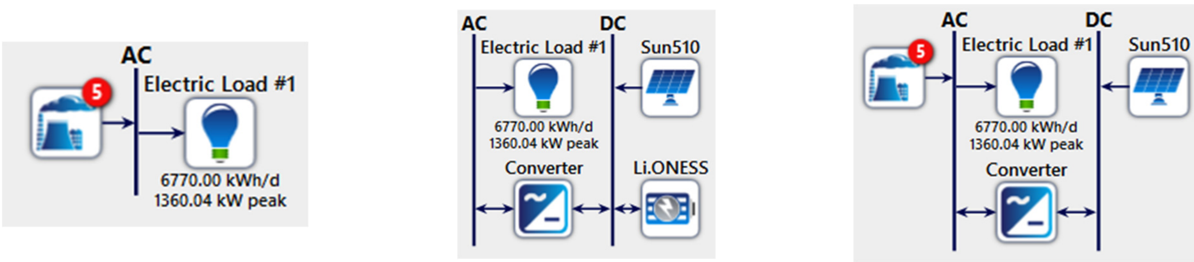


(**a**) (**b**)

Figure 2. Comparison between the systems in terms of (**a**) monthly cost and (**b**) investment cost.

3. HOMER Simulation

Three HOMER simulations were performed to further understand the system and validate the study. The HOMER software was chosen to perform the simulation owing to its wide range of applications and the large variety of systems it can model [21]. These three simulations mimicked the three systems presented previously, which are the diesel generator system, the off-grid system, and the on-grid system. Figure 3 shows schematics of the three simulated systems. Table 4 shows the load that was used for the study, which was based on the real load of BAU's Beirut campus. Figure 4 shows this load as a color plot provided by HOMER software.



(**a**) (**b**) (**c**)

Figure 3. HOMER schematics of the three systems: (**a**) diesel generator system, (**b**) off-grid system, and (**c**) on-grid system.

Table 4. Yearly profile of the load in kW.

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
0	40	69	75	83	92	60	100	98	50	83	75	69
1	40	69	75	83	92	60	100	98	50	83	75	69
2	40	69	75	83	92	60	100	98	50	83	75	69
3	40	69	75	83	92	60	100	98	50	83	75	69
4	40	69	75	83	92	60	100	98	50	83	75	69
5	40	69	75	83	92	60	100	98	50	83	75	69
6	120	208	225	250	275	180	300	293	150	250	225	208
7	200	346	375	417	458	300	500	488	250	417	375	346
8	544	941	1020	1133	1247	816	1360	1326	680	1133	1020	941
9	544	941	1020	1133	1247	816	1360	1326	680	1133	1020	941
10	544	941	1020	1133	1247	816	1360	1326	680	1133	1020	941
11	544	941	1020	1133	1247	816	1360	1326	680	1133	1020	941
12	544	941	1020	1133	1247	816	1360	1326	680	1133	1020	941
13	544	941	1020	1133	1247	816	1360	1326	680	1133	1020	941
14	544	941	1020	1133	1247	816	1360	1326	680	1133	1020	941
15	544	941	1020	1133	1247	816	1360	1326	680	1133	1020	941
16	544	941	1020	1133	1247	816	1360	1326	680	1133	1020	941
17	400	692	750	833	917	600	1000	975	500	833	750	692
18	200	346	375	417	458	300	500	488	250	417	375	346
19	120	208	225	250	275	180	300	293	150	250	225	208
20	80	138	150	167	183	120	200	195	100	167	150	138
21	40	69	75	83	92	60	100	98	50	83	75	69
22	40	69	75	83	92	60	100	98	50	83	75	69
23	40	69	75	83	92	60	100	98	50	83	75	69

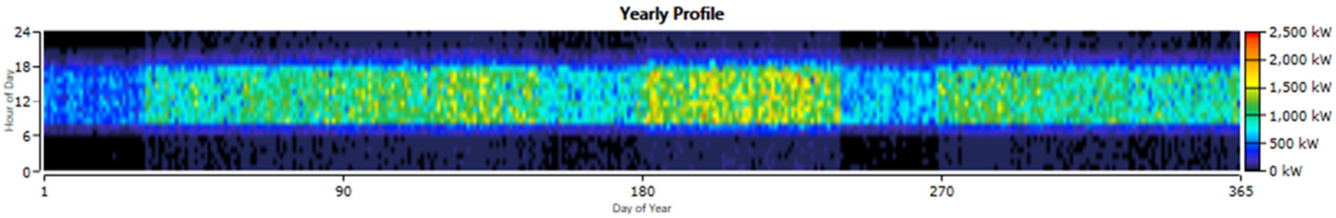


Figure 4. Yearly profile of the studied load.

3.1. Simulation of the Diesel Generator System

The first simulated scenario was the diesel generator scenario. Five generators were used here from HOMER's library with the same capacity as those present at BAU. This system represents the status quo and has no initial costs. Figure 5 shows the yearly cash flow of this scenario that was computed by HOMER. The graph shows that the diesel generator has a yearly expense of USD 668,150, which is approximately equal to the calculated value in the study of USD 670,000 after taking the holidays and the season differences into consideration. Figure 6 also shows the cumulative cash flow of this system based on the cash flow graph, which shows that if no actions are taken, the amount of money that will be paid over the years will become prohibitive.

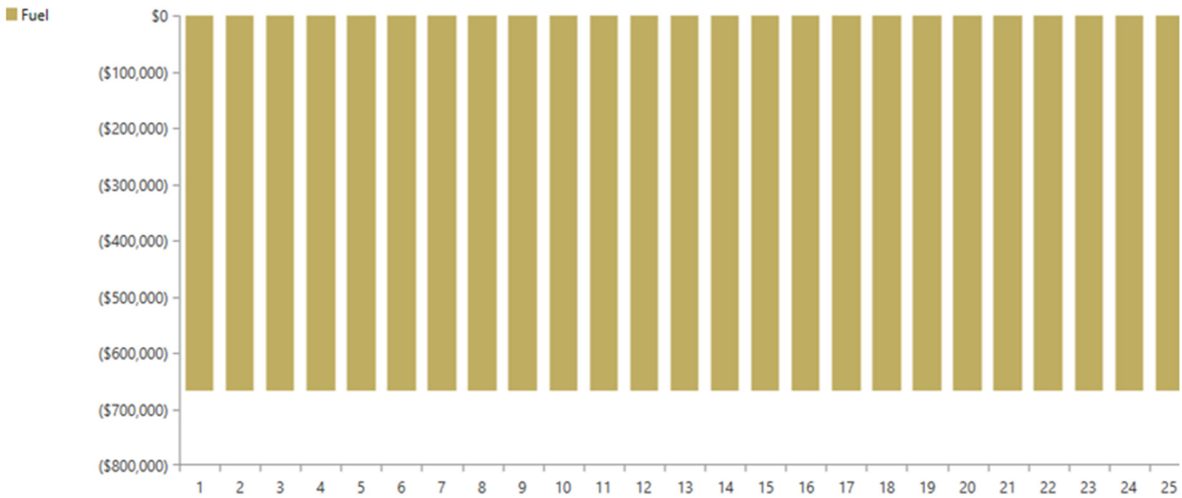


Figure 5. Cash flow graph of the diesel generator system.

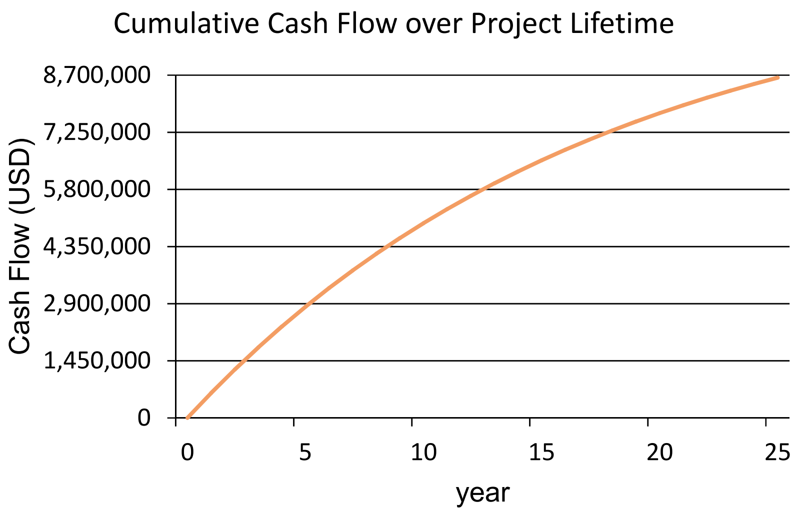


Figure 6. Cumulative cash flow of the diesel generator system.

Figure 7 shows the monthly electric production of the different generators used in this scenario, calculated using HOMER. This graph shows that the peak month (July), as well as the vacation months (January, June, and September), were considered.

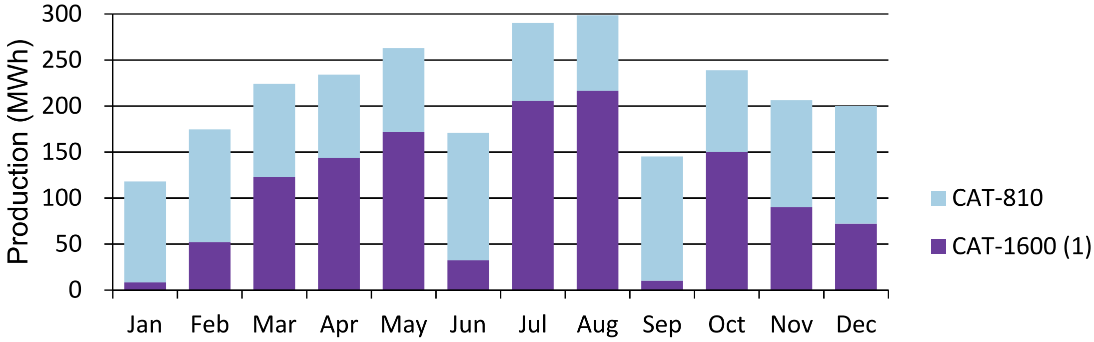


Figure 7. Monthly power generation of the diesel generator system.

Another important aspect that should be mentioned is the fuel (mainly diesel) consumed by the system, as well as the emissions resulting from burning this fuel. Tables 5 and 6 present the HOMER results of the amounts of fuel consumed and the resulting gas emissions, respectively. These two tables show that this system has high emissions, which is obviously undesirable from environmental and health perspectives.

Table 5. Fuel consumed in the diesel generator system.

Quantity	Value	Units
Total fuel consumed	835,176	L/year
Average fuel per day	2288	L/day
Average fuel per hour	95.3	L/hour

Table 6. Gas emissions of the diesel generator system.

Quantity	Value	Units
Carbon Dioxide	2,205,901	kg/year
Carbon Monoxide	1419	kg/year
Unburned Hydrocarbons	506	kg/year
Particulate Matter	196	kg/year
Sulfur Dioxide	5475	kg/year
Nitrogen Oxides	14,121	kg/year

If a single car emits 4600 kg/year of CO_2 [22], then in this scenario, the university will be equivalent to the addition of 480 cars to the streets in Beirut. Therefore, continuing with the current situation might seem appealing for the time being, but in the long run, it will be extremely costly, which might hinder BAU's growth while also imposing health and environmental hazards due to the large amounts of emissions produced.

3.2. Simulation of the Off-Grid System

The second scenario studied was an off-grid system. In this system, the entire load is supplied purely by solar energy, while a battery storage system is added to support the load when the sun is absent. This system has approximately no operating cost in comparison with the other studied scenarios, but at the same time, as computed by HOMER and similar to the previously calculated value, the cost of this system, including the panels, inverters, batteries, and connections, is approximately USD 5.07 million, which is too high for investment and has a long payback time. Figure 8 shows the cash flow graph of this scenario, which consists of only the investment and replacement costs. Additionally, Figure 9 shows the cumulative cash flow of this system, which continues to be higher than the graph given in Figure 6 until around year 11, validating the payback period computed in the feasibility study.

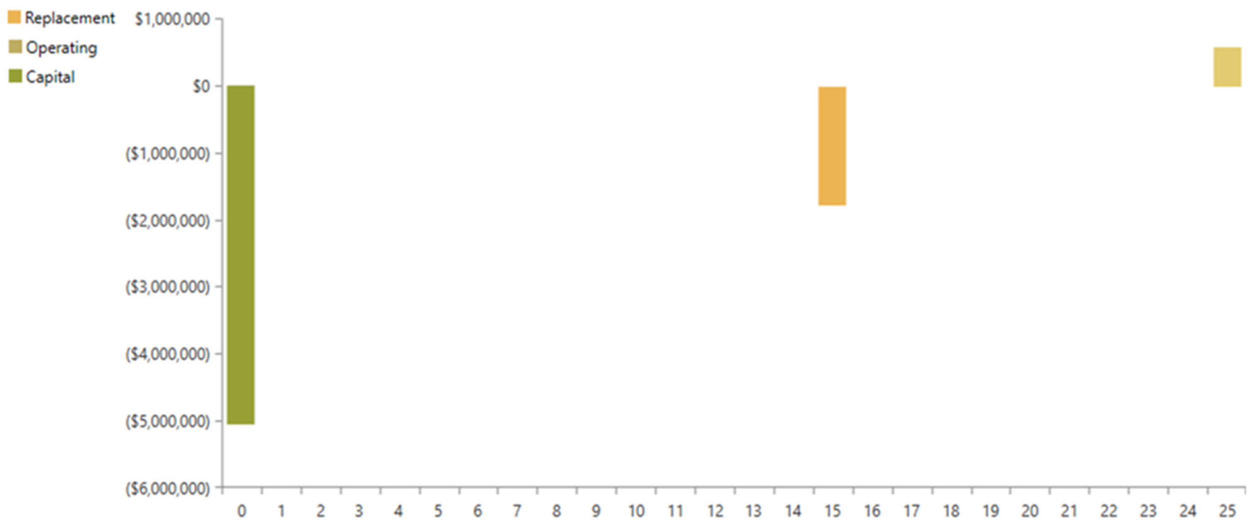


Figure 8. Cash flow graph of the off-grid system.

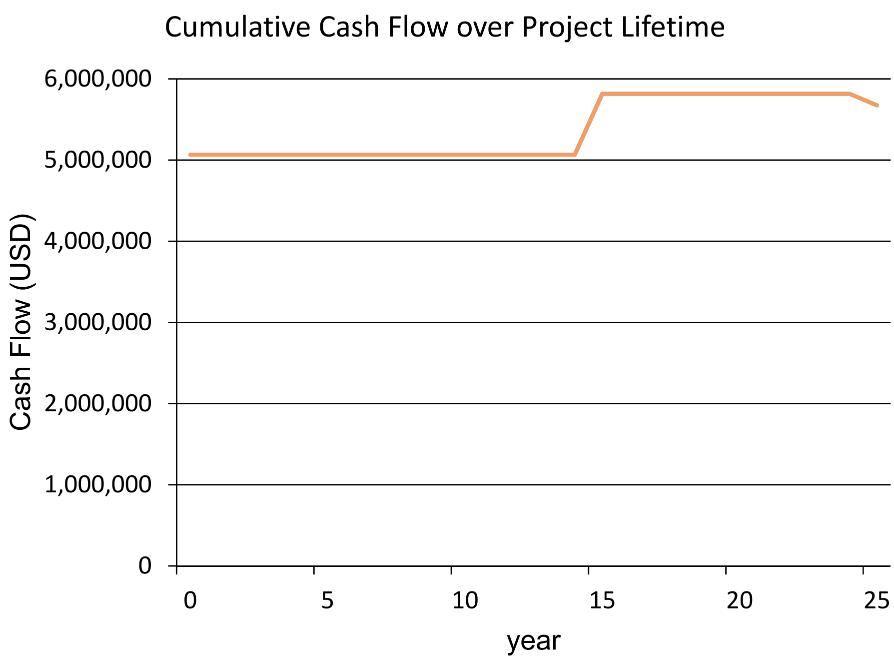


Figure 9. Cumulative cash flow of the off-grid system.

Figure 10 shows the power production of the off-grid system and the extra production needed in this system compared to the previous one. The main reason for the need for this extra production is that in the off-grid system, it is necessary to both supply the load and charge the batteries.

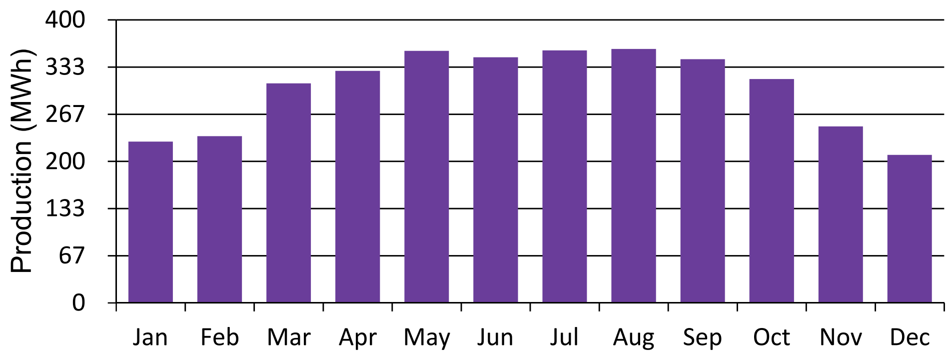


Figure 10. Monthly power generation of the off-grid system.

One more concern to be taken into consideration when having batteries in the system is their state of charge, which is also calculated by HOMER and provided in Figure 11. This graph shows that, on average, the maximum depth of discharge that the system may reach is approximately 50%, which is below the 90% depth of discharge of LiFePO4 batteries.

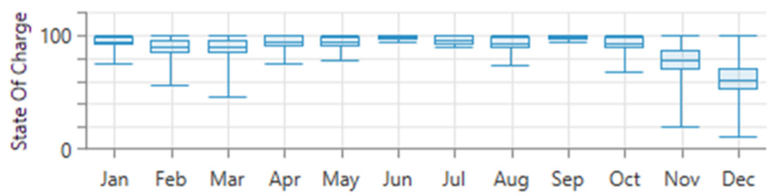


Figure 11. State of charge of the batteries around the year.

It is also worth noting that this scenario has no emissions, which is ideal for the environmental and health aspects. In conclusion, this scenario has many advantages. From a sustainability perspective, it is ideal, but the investment cost here is too high, and the payback period is too long, making this scenario unfeasible from an economic perspective. Moreover, in case of consecutive cloudy days, the system will be off due to a lack of sun, hence lowering the reliability of the power system, which may cause damage to critical loads such as servers, medicine refrigerators, and some equipment in laboratories.

3.3. Simulation of the On-Grid System

The third and final scenario to be simulated is the on-grid system. In this system, both the PV array and diesel generators supply the load simultaneously. According to HOMER's calculations, which came in conjunction with the calculations presented in the study, the initial capital investment of this project was approximately USD 330,000, with an operational cost of USD 491,000 for the diesel generators' fuel and maintenance. The complete cash flow graph is presented in Figure 12, with Figure 13 giving the cumulative cash flow graph of the system to better understand the economics of this system in the long run, which shows that even after 25 years, the money spent would be less than in the other two systems presented in Figures 6 and 9.

Figure 14 shows the monthly power generated by the generators and the solar array. It shows that the amount of generated power is similar to that of the first system due to the absence of the need to charge any batteries, but at the same time, it shows the contribution of the PV array to power generation, which reduces the burden on the generators.

An important issue to address in the case of the diesel generator system is fuel consumption and the resulting emissions. Tables 7 and 8 list the amount of diesel consumed and the resulting emissions, respectively. These two tables, when compared with those presented in the first scenario, show a significant reduction in both fuel consumption and emissions.

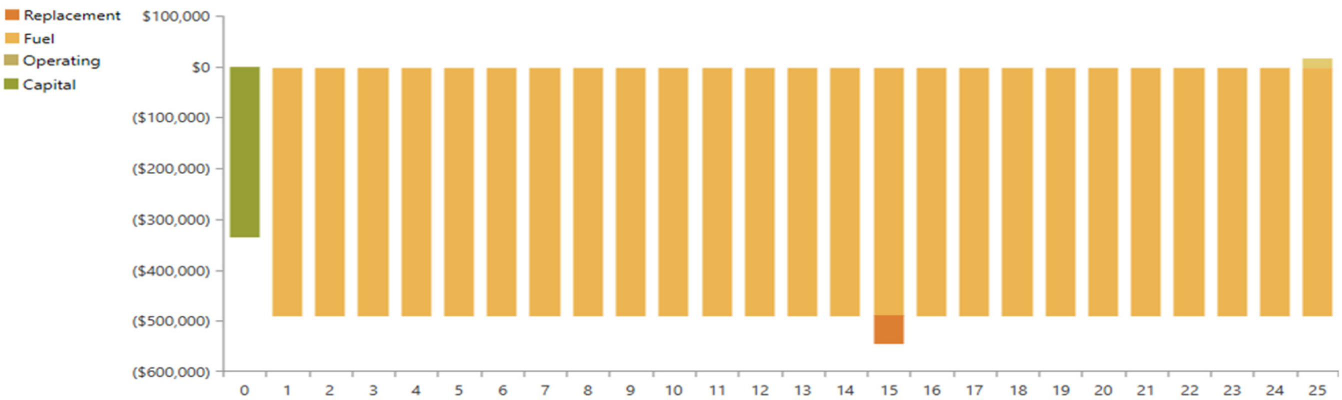


Figure 12. Cash flow graph of the on-grid system.

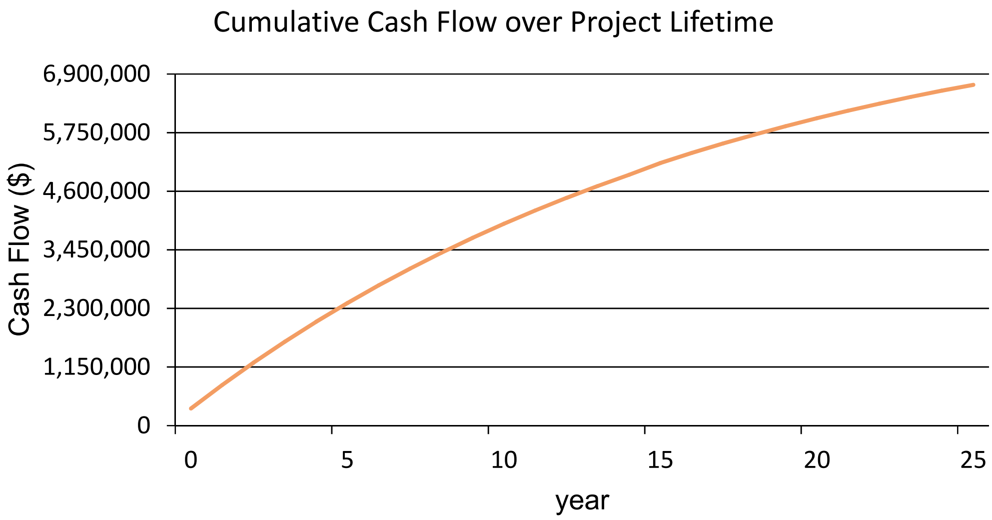


Figure 13. Cumulative cash flow of the on-grid system.

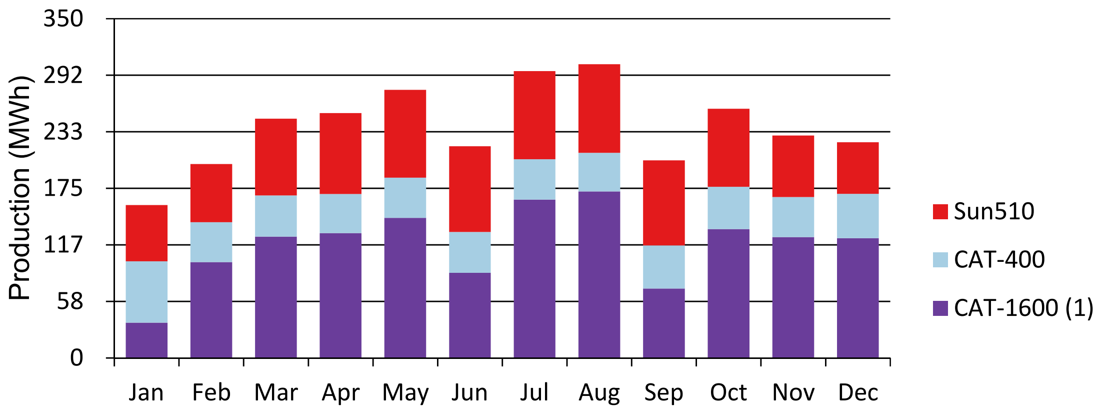


Figure 14. Monthly power generation of the on-grid system.

Table 7. Fuel consumed in the on-grid system.

Quantity	Value	Units
Total fuel consumed	612,389	L/year
Average fuel per day	1678	L/day
Average fuel per hour	69.9	L/hour

Table 8. Gas emissions of the on-grid system.

Quantity	Value	Units
Carbon Dioxide	1,617,031	kg/year
Carbon Monoxide	1594	kg/year
Unburned Hydrocarbons	236	kg/year
Particulate Matter	90.8	kg/year
Sulfur Dioxide	4015	kg/year
Nitrogen Oxides	9750	kg/year

The emissions in this scenario are equivalent to 352 cars. Therefore, when comparing this result with the one in the diesel generator system, which is equivalent to 480 cars, we deduce that by implementing the on-grid system, we can remove emissions equivalent to the removal of 128 cars from the streets with a fairly low investment cost. This scenario is logical in terms of health, environmental, and economic aspects.

As shown from these simulations, adopting the diesel generator system incurs no initial costs, but the operating and fuel costs are far too high, and emissions are significant. As for the off-grid system, the operating and fuel costs are negligible in comparison with the other two systems for the amount of emissions, which makes it favorable environmentally and health-wise, but its investment cost is too high, and its return-on-investment time is too long, making it economically unfeasible and with low power system reliability. For the on-grid system, the amount of consumed fuel and emissions are moderate in comparison with the generator-only scenario while maintaining an acceptable investment cost and preserving system reliability. This, in agreement with the results obtained in the feasibility study, indicates that the on-grid system is the optimal solution for the electricity problem in BAU, and based on this, BAU adopted this solution and implemented it on its Beirut campus.

4. Implementation

As concluded in the previous sections, an on-grid solar system coupled with diesel generators is the most feasible solution for the electricity problem in both the short and long terms. As a result, BAU implemented an on-grid solar system on its Beirut campus. An overview of the different parts of the implemented system is given in this section.

4.1. Diesel Generators

The five diesel generators present at BAU have a combined generation capacity of 4500 kVA. Figure 15 shows one of those existing generators. It should be noted that the capacity of the generators was designed to follow the 2N + 1 redundancy standard to ensure optimal reliability.

Figure 15. Main body of the larger generator.

A specialized control system is used to turn the generators on and off properly, based on both the changes in the load and the power generated by the solar system. This system, as shown in Figure 16, is placed inside a metal compartment to protect it from external factors and interference.

Figure 16. Control system coupling the five generators.

4.2. PV Panels

The panels used in this system are the Trina 550 W modules with the specifications presented in Table 9.

Table 9. Specifications of Trina solar panels.

Quantity	Value
Pmax	550 W
Vmp	31.6 V
Imp	17.4 A
Voc	37.9 V
Isc	18.52 A
Maximum series fuse	30 A
Power selection	0 ± 5 W
Maximum system voltage	IEC 1500 V

These panels are spread all over the roofs of the facilities present at BAU at different angles to capture the most available solar radiation throughout the day (see Figure 17). This spread also helps make utmost use of the limited area available.

4.3. Inverters

In this system, nine 50 kW, SMA on-grid inverters are coupled together and then synchronized with the diesel generators via a DEIF controller to feed the required load throughout the day. Figure 18 shows the inverters used in the real system. It is worth mentioning that the inverters were positioned in different places all over the campus close to the PV sub-arrays to minimize losses during transmission as much as possible.

4.4. Functionality

This system has proven to be able to feed the load even during winter days when the sun's angle is low and the days are short. Figure 19 shows the generation details of the controller used to monitor the system at 10:30 am on 1 December 2022. We can see that, for a total load of 300 kW (representing only the main building), the solar system supplies 67% of the load at a power factor of 86%.

Figure 17. The complete solar array installed at BAU Beirut campus.

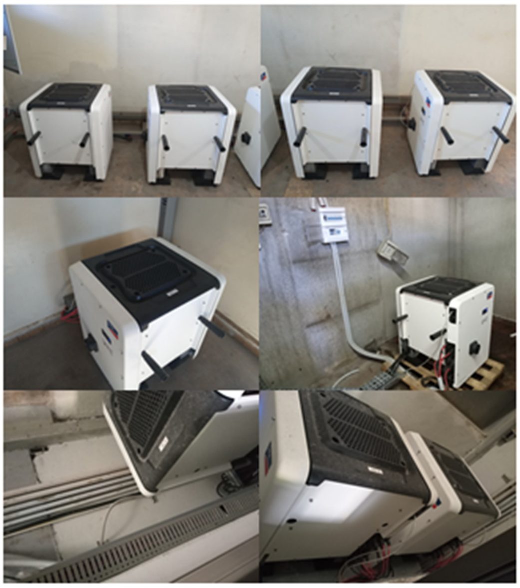


Figure 18. The installed inverters.

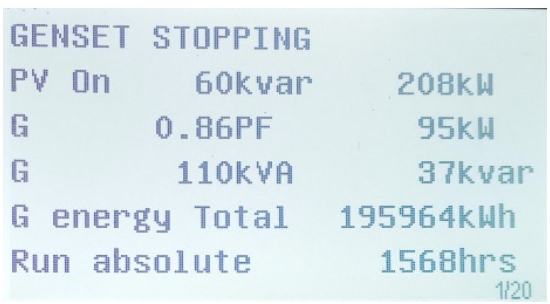


Figure 19. Controller display showing the actual generation of the on-grid solar system.

5. Conclusions

Lebanon has always been hanging on the verge of collapse and has started falling in recent years. Prices are skyrocketing because of the local currency's deteriorating value. Amidst this, the electrical power supply has become a memory owing to the tremendous leap in fuel prices. As for BAU, for which electricity is an indispensable necessity, finding a solution for the electricity problem took priority above all else. In this study, three systems that can solve the problem were studied, the first of which is continuing with the current solution and continuing to rely on the originally present diesel generators, which proved to be impractical owing to the high fuel and operating costs as well as the health and pollution issues associated with it. The second scenario consists of an off-grid solar power system, which is considered the best solution in terms of sustainability and environmental aspects but was considered unfeasible because of the high investment cost of USD 5,095,000 as well as the very long payback period of 11 years, the low system reliability, and the area needed. The third scenario suggested an on-grid system by coupling a solar system with the already present diesel generators; this solution has a relatively low cost of USD 330,000 and, at the same time, decreases the stress on the generators, which cuts down on fuel and operation costs. Therefore, it is considered to be the most feasible solution. To further validate and understand the system, HOMER simulations of the three studied scenarios were performed, and the obtained results were consistent with the results obtained in the scenarios and feasibility studies. In addition, as shown by HOMER, the emission reduction caused by applying the on-grid system was equivalent to removing 128 cars while maintaining a relatively low investment cost. These results confirm that, in comparison with the first two scenarios, the on-grid solution strikes a balance between initial investment, payback time, and emission reduction. Regarding the implementation aspect, the system's power output was 208 kW in December. It is anticipated that the system will achieve its maximum output of approximately 450 kW by June, based on prevailing weather conditions. We anticipate that the outcome of this study will inspire and motivate other organizations and communities to embrace sustainable and renewable energy sources as viable alternatives to traditional energy sources. This shift in approach would have a positive impact on the environment and promote a more sustainable future.

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