Economic Feasibility and CO_2 Emissions Analysis of Solar Parking Lot vs. Diesel Generator as Backup Power System: A Case Study

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Rising electricity demand increases reliance on carbon-intensive sources, harming the environment. Solar energy offers a cleaner alternative, but choosing between a solar parking system and a diesel generator is complex due to differences in operation, investment, and revenue potential. Studies comparing these under multiple economic scenarios and CO_2 emissions are limited. This study presents an integrated economic and environmental comparison of a grid-connected solar parking system versus a diesel generator for Qom University of Technology. The solar system was designed for the existing parking layout, using Meteonorm data, PVsyst simulations, and PV*SOL for emissions. Diesel output and fuel use were based on its operating schedule. Both were evaluated under four economic scenarios varying service life, replacements, and revenues. Annual output was 120.35 MWh (solar) and 21.12 MWh (diesel). Scenario 4; including electricity sales and lighting revenue; yielded the best economics. Over 20 years, future value was $63,273.88 (solar) versus $50,261.42 (diesel). Solar generated ~$2,328 annual revenue, with levelized energy costs of $0.0243/kWh versus $0.094/kWh for diesel. Though solar required higher upfront investment, it became more attractive when electricity could be sold. Environmentally, diesel emitted 13,531 kg CO_2/year, while solar avoided ~56,564 kg/year. Overall, the best choice depends on conditions, but under monetization scenarios, solar offers substantial long-term economic and environmental benefits.

Keywords: *Economic Feasibility, Diesel Generator, Solar Parking Lot, CO_2*

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Nomenclature

PV	Photovoltaic
EVs	Electric vehicles
LED	Light-Emitting Diode
PEVs	Plug-In Electric Vehicles
LCC	Life cycle cost
PP	Payback period
NPV	Net present value
IRR	Internal rate of return
LCA	Life cycle assessment
GIS	Geographic information system
RPM	Revolutions per minute
FV	Future value
P	Initial price
i	Interest rate
A	Annual cost or revenue
n	Project's lifetime
Capex	Capital Expenditure
Opex	Operational Expenditure
O&M	Operations and Maintenance
D	Diesel generator
SP	Solar parking
AGE	Annually generated electricity
LCOE	Levelized cost of energy
IC	Initial costs
IR	Interest rate
LF	Lifetime
$C_{annual,PV}$	Annualized cost of the PV system
C_{PV}	Normalized cost of PV-generated electricity
$C_{annual,diesel}$	Annualized cost of the diesel-generator system
C_{diesel}	Normalized cost of diesel-generated electricity
P_{backup}	Average backup power

E_{usable} Required usable backup energy

$E_{nominal}$ Required nominal battery capacity

1. Introduction

Energy is one of the most important variables impacting all economic operations. Energy economics, according to Subhes C. Bhattacharyya, comprises issues concerning energy supply and use in society. As a result, it is critical to apply this discipline of study to the advancement of society. Energy economics became active in the 1980s[1]. The growth of the world's population and the development of various economic sectors have boosted the use of energy carriers and increased attention to renewable technologies for delivering electric energy.

Renewable energy sources provide more than 22% of the world's electricity[2]. By 2100, the share of renewable or alternative energy sources to electrical generation is expected to reach 80%[3]. Among the benefits of employing renewable energies for sustainable development are increased energy security and economic development, slowed climate change, and reduced harmful environmental impacts[4]. Hydropower, wind, biomass, geothermal, marine, and solar energy are all examples of renewable energy. Two types of solar power plants utilize solar energy: solar thermal and photovoltaic (PV). In heliostat, linear parabolic trough, solar chimney, parabolic dish, and Fresnel collector power plants, focused solar radiation raises the temperature of the working fluid, while PV power plants directly convert solar energy into electricity[5].

PV systems stand out among current distributed energy solutions as the most accessible and abundant resource for power generation, contributing considerably to the Earth's energy production[6]. Depending on their intended use—such as lighting, powering water pumps, or serving as backup systems—PV systems can be either grid-connected or off-grid. One emerging application is the integration of solar panels into parking lots, which has been recently explored[7]. These parking spaces can be utilized to power electric vehicles (EVs) and battery-charging backup systems, as well as to supply electricity to a building[8, 9].

Safarpour et al.[10] explored solar panel adoption in sports stadiums, revealing barriers like high costs and technical gaps, alongside benefits such as emissions reduction and energy savings. Through expert interviews, they proposed solutions like solar carports and LED lighting, demonstrating solar energy's role in sustainable stadium design.

Iringová & Kovačić[9] designed and optimized a PV system for a parking garage in Žilina, Slovakia, to enhance solar energy efficiency and support electric vehicle (EV) charging infrastructure. The study evaluated three PV panel technologies (monocrystalline, polycrystalline, and amorphous silicon) under varying inclinations (0°, 37°, 90°), identifying monocrystalline panels at a 37° tilt as the most efficient, yielding 74,968 kWh/year—enough to power six EV charging stations and reduce grid electricity consumption by 9.14%. Despite a 17-year payback period, the system aligned with EU sustainability goals, demonstrating the viability of integrating PV systems into urban infrastructure to cut emissions and promote renewable energy use.

Tulpule et al.[11] conducted an energy-economic analysis of a PV-based charging station for Plug-In Electric Vehicles (PEVs) at workplace parking garages, focusing on two locations with varying solar radiation and financial structures: Columbus, OH, and Los Angeles, CA. They performed hourly energy simulations and cash flow analyses, incorporating factors such as vehicle types, driving patterns, parking times, and financial incentives like tax rebates. The study evaluated the feasibility of PV-based charging, its economic impact on both garage owners and vehicle owners, and its environmental benefits, including reduced grid emissions. The results demonstrated that PV-based workplace charging could significantly lower CO_2 emissions (up to 68% compared to nighttime home charging) and achieve financial viability, with payback periods ranging from 11 to 15 years depending on location and parking rates.

Leon Marquez in his master's thesis [12] investigated a case study on the Austin FC Stadium to evaluate green strategies for reducing its carbon footprint, focusing on energy-related emissions from electricity and natural gas consumption. They analyzed three key alternatives: installing low-wattage floodlighting systems, implementing a solar PV carport system, and replacing natural gas-fueled furnace heating with electric heat pumps. Using energy modeling tools like eQUEST and PVWatts, they simulated hourly energy demand and generation, while also considering financial factors such as abatement costs, incentives, and electricity rates. The results showed that the proposed strategies could reduce the stadium's carbon footprint by up to 32%, with the solar PV carport system offering the most significant emissions reduction (20%), followed by energy-efficient lighting (4%) and heat pumps (15%). The study highlighted the trade-offs between cost and emissions savings, emphasizing the importance of aligning green strategies with climate goals and financial feasibility.

Many societies still give diesel generators top priority as backup systems even with notable developments in solar systems. Diesel generators have many benefits, one of which is their capacity to provide continuous power. From an economic point of view, fossil fuel generators and PV systems have been examined. Sami [13] conducted an economic feasibility study comparing a 2kW solar PV system with a 2kW gasoline generator for electricity generation in Iraq. Using life cycle cost (LCC) and payback period (PP) analyses, the author demonstrated that the solar PV system had a significantly lower LCC ($6,156) compared to the gasoline generator ($12,110) over a 20-year lifespan, despite the PV system's higher initial cost. The study highlighted that the solar system's payback period was 12 years, with net benefits of $3,780 due to savings on fuel and maintenance. Sami concluded that solar PV systems are economically viable and environmentally preferable for Iraq, given its abundant solar resources and the high operational costs of fossil fuel-based generators.

Babajide and Brito [14] investigated the feasibility of using solar PV systems as a cleaner and more reliable alternative to diesel generators for electricity generation in Lagos, Nigeria, where power outages are frequent. They analyzed real data from a monitoring campaign to assess household electricity consumption and designed solar PV systems tailored to urban households' needs. By comparing the costs of diesel generators and solar PV systems, they demonstrated that solar PV systems could reduce or eliminate diesel generator use, achieving cost savings of 60–65% over the project lifetime. Their results highlighted the potential for solar PV systems to be financed through fuel savings, making them a financially viable and sustainable solution for improving electricity access while mitigating health and environmental risks associated with diesel generators.

Mahmoud and Ibrik [15] conducted a techno-economic feasibility study comparing three energy supply systems—solar PV, diesel generators, and electric grid extension—for electrifying the remote village of Atouf in Palestine. They designed each system, calculated associated costs, and evaluated their economic viability using dynamic financial indicators such as net present value (NPV), internal rate of return (IRR), and cost annuity. Their results demonstrated that the PV system was the most economically feasible option, with lower energy production costs (2.28 NIS/kWh) compared to diesel generators (2.76 NIS/kWh) and grid extension (3.06 NIS/kWh). Additionally, the PV system had a shorter dynamic payback period and minimal environmental impact, making it the optimal solution for rural electrification in similar regions.

Olczak et al. [16] evaluated the environmental and economic impacts of Poland's *"My Electricity"* subsidy program, which promoted residential PV installations from 2019 to 2020. The authors conducted a life cycle assessment (LCA) to quantify CO_2eq emissions avoided by replacing fossil fuel-based electricity (coal, lignite, natural gas, and Poland's energy mix) with solar energy. They analyzed 226,454 PV installations (totaling 1.295 GWp) funded by the program, finding these systems would produce 38 TWh of electricity over 30 years while avoiding 26.2–42.7 million Mg of CO_2 eq emissions, depending on the replaced energy source. The study highlighted the program's cost-effectiveness, with a subsidy expenditure of 6.52 EUR/MWh and projected savings of EUR 1550 million in avoided CO_2 emission permits. The results underscored the program's success in accelerating Poland's energy transition despite its coal-dominated grid.

Recent research has broadened the analysis of energy and environmental systems to include climate-sensitive renewable-energy planning, organizational energy management, intelligent decision-support tools, and life-cycle environmental assessment. A comparative study of solar-energy development in Iran investigated the effects of climatic conditions on PV performance and underscored the need to account for regional variations when evaluating solar-energy systems [17]. At the institutional level, a global review of ISO 50001 proposed a framework for strengthening energy-management systems in Iran, emphasizing systematic planning, performance monitoring, and continuous improvement [18]. Artificial intelligence has also emerged as an important tool in modern energy systems, supporting forecasting, fault detection, system optimization, and data-driven decision-making [19]. In environmental assessment, an LCA-based comparison of electric and internal-combustion-engine vehicles under different ambient-temperature conditions highlighted the importance of clearly defining climatic assumptions, system boundaries, and functional units in comparative studies[20].

Previous studies have demonstrated that Iran has considerable potential for photovoltaic electricity generation and that PV system performance should be assessed in relation to the climatic characteristics of each region. However, research on solar parking facilities has predominantly focused on technical design, electricity-generation potential, and electric-vehicle charging applications. Similarly, comparative studies of PV systems and conventional generators have largely been confined to residential, rural, or off-grid contexts.

Addressing this gap, the present study investigates a real institutional energy-planning case at Qom University of Technology, where electricity is required during specific daytime hours in summer. A grid-connected solar parking system was designed in accordance with the physical layout and climatic conditions of the site and compared with a diesel generator capable of meeting the same operational requirement. Rather than evaluating the two alternatives under a single set of economic assumptions, the analysis considers four scenarios representing different project lifetimes, diesel-generator replacement requirements, and approaches to valuing solar electricity through on-site consumption and grid sales.Site-specific meteorological data were obtained from Meteonorm. The solar parking system was designed and its electricity output was simulated using PVsyst, while PV*SOL was employed to estimate avoided CO_2 emissions and account for first-year module degradation. For the diesel generator, electricity generation, fuel consumption, operating costs, and direct CO_2 emissions were calculated separately based on its technical specifications and assumed operating schedule. The economic assessment included both future value and levelized cost of energy, while the environmental assessment compared the emissions generated or avoided by the two systems.

A supplementary equal-energy analysis was also conducted to compare normalized costs and emissions per usable kilowatt-hour. This analysis was included to account for the fundamental operational distinction between grid-connected PV generation, which depends on solar availability, and diesel generation, which provides dispatchable backup power.

The principal contribution of this study is the development of a site-specific, scenario-based decision framework that integrates the physical design of a solar parking facility with long-term economic performance, equipment-replacement requirements, electricity-monetization options, operational characteristics, and CO_2 impacts. Whereas previous studies have often applied selected economic indicators, such as life-cycle cost, payback period, net present value, and internal rate of return, or have examined environmental impacts separately, the proposed framework brings these economic, operational, and environmental dimensions together within a unified assessment.

A key advantage of this framework is that it evaluates the preferred alternative under varying project lifetimes, replacement conditions, and electricity-monetization assumptions rather than relying on a single fixed scenario. Nevertheless, the analysis remains specific to the case-study site and does not include a full life-cycle assessment or probabilistic uncertainty analysis. Despite these limitations, the framework provides a practical basis for institutional energy-planning decisions in regions with favorable solar resources.

2. Solar System and Diesel Generator

The national power network experiences lower demand during off-peak hours, and internal grids require a method to manage the reduced load. In June, July, and August, the inspected lot needed electricity from 11 AM to 2 PM.

2.1. Solar system

With 300 sunny days per year, Iran is one of the countries with high potential for solar energy generation. The Solar GIS site's map of the irradiation potential of various locations worldwide depicts the irradiation received per square meter of the Earth's surface. According to this map, Iran's geographic location results in an average of 5.5 hours of sunlight each day throughout the year. The sun shines differently on various parts of the planet depending on Earth's annual motion during different seasons. As previously mentioned, power is generated by the backup system during peak sunlight hours in the summer. As a result, the backup solar system can be a grid-connected system that does not require a battery. The site under consideration is Qom University of Technology, which is located in Qom Province. The meteorological specifications for the region, based on Meteonorm software, are presented in Fig. 1.

The Qom province is arid and warm, with a high mean summer temperature (Fig. 1a). Its relatively high mean received irradiance, particularly in June, July, and August, demonstrates the region's suitability for solar power plant construction (Fig. 1b). During these months, the day can last up to 11 hours on average. The use of solar systems in urban areas faces various obstacles, including shade from buildings and vegetation on PV panels, as well as the necessity for large installation areas [9].

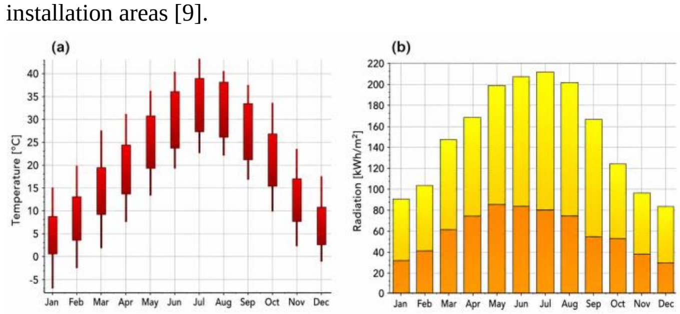

Fig. 1. a) Mean temperature of Qom province, b) Mean received irradiation of Qom province.

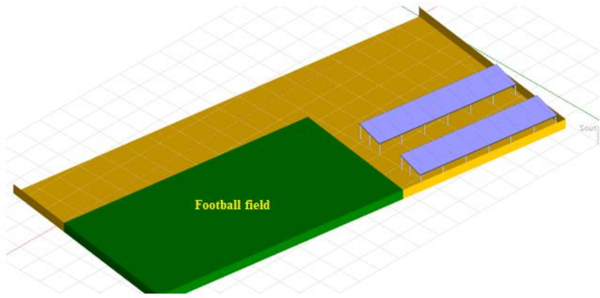

Fig. 2. Sketch of the solar parking lot.

Table 1. Main technical specifications and operating assumptions of the two systems.

Parameter	Value used in the study
PV module	TABAN TBM72-390M, PERC monocrystalline, 72 cells
Module rated power and efficiency	390 Wp and 20% at STC
PV array configuration	180 modules, 70 kW, 15° tilt
Inverter configuration	Fronius grid-connected, three-phase, transformerless inverters with multiple MPPTs and different power ratings
Maximum inverter efficiency	Approximately 98%
Main PV loss factors	Module-temperature loss, ohmic wiring loss, module-quality loss, and inverter-conversion loss
Shading	Row spacing was considered in the layout; simulated annual shading loss was approximately 0.8%
Module degradation	1.36% in the first year, as estimated by PV*SOL
Diesel-generator model	Perkins 1104C-44TAG2 diesel generator set
Generator rating used in the study	110 kW
Generator load profile	June–August, from 11:00 to 14:00; approximately 300 h/year
Fuel-consumption assumption	17.1 L/h
Actual average generator loading	70.4 kW, equivalent to approximately 64% of rated capacity

The construction of a solar parking lot eliminates the shading issue and optimizes the use of the panel-occupied area. The PVsyst program was used to design the 70 kW solar parking lot. Typical measurements for a parking lot had to be considered during the design process, which requires a minimum height of 2.2 m. The supports were positioned 5 m apart, the maximum distance allowed for parking two cars. Theoretically, the optimal tilt for maximum annual irradiance at 34.6°N latitude is approximately 34°. However, mounting modules at this steep angle over a shaded parking space would result in excessive height and structural costs. Additionally, the yearly energy yield at 34° is only 2–3% higher than at 15°. Therefore, a 15° tilt was selected not only to achieve nearly equivalent solar power generation but also to maximize shaded space for parked vehicles beneath the canopy. The panel slope was set at 15°, and the required area was 540 m². The layout was planned to ensure that the front lines of the panels did not cast shadows on the back rows. According to the dimensions provided, the solar system requires a total of 180 PV panels. Fig. 2 depicts a schematic of this solar parking lot. There are two lines in the solar parking lot described above, each with ninety PV panels (Fig. 2). The 144 MWh of initial electricity produced by the panels passes some losses in the collector-to--inverter link: PV loss due to temperature, Ohmic wire loss, module quality loss, and inverter loss during operation.

2.2. Diesel generator

Diesel generators are among the sources of emergency electricity used today. This section investigates the use of a diesel generator as a backup solution for the site under consideration. There are several types of diesel generators available in the market, each with varying prices. For this study, a 110 kW Perkins generator, model Perkins 1104C-44TAG2, made in England, was selected. High revolutions per minute (RPM) is an extremely important feature in diesel generators, as it enhances efficiency; that is, diesel generators with high RPM consume less energy to generate electricity. Other advantages of these generators include their reduced weight (987 kg) and smaller dimensions (1.8 × 1.1 × 2.7 m) compared to similar models. Additionally, this brand of generator utilizes water as a cooling system. Over the year, the chosen generator is expected to generate electricity for 90 days (three hours each day). In other words, the generator will run for approximately 300 hours each year. Table 1 summarizes the main technical specifications and operating assumptions considered in the simulation and analysis of the solar parking system and the diesel generator.

3. Economic Analysis

Azadnia [21] defines the economic comparison of industrial projects as requiring a set of mathematical methodologies provided by engineering economics. As a result, it is critical to assess both the technical and economic feasibility of a project to select the best and most cost-effective design based on accurate and reliable results. One of the economic metrics in project analysis is the present value, or the current worth of cash [22]. Another economic metric covered in this study is the future value (FV), which represents the future value of all revenues and present costs of a project concerning the interest rate and is computed using the equation below[22]:

$$FV = -P(F/P, i\%, n) \pm A(F/A, i\%, n) \tag{1}$$

FV is the future value, *i* is the interest rate, *P* is the initial price, *A* is the annual cost or revenue, and *n* is the project's lifetime.

The interest rate, also known as the minimum attractive rate, is the risk-free interest rate that equals the profit rate of exchange corporate bonds and National Development Fund facilities in the energy industry. This rate is estimated to be 8%. Capital Expenditure (Capex) refers to the costs of equipment, services, transportation, and more, whereas Operational Expenditure (Opex) refers to the costs incurred by the project over its lifetime, such as operations and maintenance (O&M), fuel, and labor costs. The levelized cost of energy is the price of producing electricity from a source, calculated by dividing the total cost over the lifespan by the total amount of electrical energy produced over that time[23].

3.1. Costs of the solar parking lot

• Capex: $50,000 is the total cost of purchasing the solar parking lot. In addition, there are costs for installation ($1,250) and transportation ($37).

• Opex: The PV power plant's continuous operating and maintenance costs are comparatively low and include the following:

i) Water Usage: Water is needed to clean the solar panels. Using a water cost coefficient of 1.39 (which represents the water cost in the Qom region) and assuming monthly panel washing, the monthly water cost for the 20 liters of water required for each wash is $3.50.

ii) Worker Cost: In Iran, a worker must make at least $4.40 per day. The annual worker cost comes to $52.80 if each cleaning operation is performed on one working day per month.

3.2. Costs of Diesel generator

- Capex: The diesel generator has a purchase price of $12,000, along with installation costs of $625 and transportation expenses of $50.
- Opex:

i) Fuel cost: Diesel fuel is available in Iran at a price of approximately $0.015 per liter. From the technical specifications of the generator, the fuel consumption of the generator is 17.1 liters per hour. The generator operates for over 300 hours annually; the approximate annual fuel cost is calculated as follows:

$$17.1\frac{lit}{h}\times 0.015\frac{\$}{lit}\times 300\frac{h}{year}=76.95\frac{\$}{year} \tag{2}$$

ii) Lubricant Cost: The engine of the generator produces heat, causes wear on components and generates metal-to-metal friction while running; therefore, lubricants should be used to prevent these issues. The efficiency and lifespan of the generator are enhanced by traditional lubricants. Since Iranian diesel fuel contains approximately 0.8% sulfur content, the lubricant for this type of generator should be changed every 100 hours. The price of lubricant in Iran averages $0.875 per liter, and the generator requires 0.054 liters of lubricant each hour. Thus, the annual cost of lubricant is $14.175.

$$0.054\frac{lit}{h}\times 0.875\frac{\$}{lit}\times 300\frac{h}{year}=14.175\frac{\$}{year} \tag{3}$$

Other O&M costs: Additional operating and maintenance costs include regular inspections, servicing every 100–150 hours of operation, servicing every 500 hours of operation, servicing every 2,000–2,500 hours of operation, and servicing every 4,000–5,000 hours of operation, as well as the replacement of air and oil filters. These costs amount to approximately 5% of the overall annual purchase price. Table 2 reflects the prices of the diesel generator, solar parking lot, and specified equipment. It should be noted that Capex is only paid once at the beginning of the project, whereas Opexs are incurred each year throughout the entire duration of the project's operation.

Table 2. Diesel generator and solar parking costs.

	Capex			Opex		
	Purchase cost ($)	Transport cost ($)	Installation cost ($)	Fuel cost ($)	Lubricant cost ($)	Other costs ($)
Diesel generator	12000	50	625	76.95	14.175	12000 × 5% = 600
Solar parking lot	50000	37	1.250	0	0	56

3.3. Examining Different Scenarios

Four scenarios are compared in the solar system and diesel generator projects. It should be noted that the generator produces electricity only when it is needed, specifically in June, July, and August from 11 AM to 2 PM in all scenarios, whereas the solar system produces electricity continuously throughout its lifetime. It should be emphasized that the comparison presented in this study is decision-oriented and based on a specific case study. Both systems are assessed as practical alternatives for addressing the same institutional power-supply challenge at Qom University of Technology. However, they differ considerably in terms of their operating principles. The diesel generator functions as a dispatchable backup source for short-duration electricity supply, whereas the solar parking system operates as a grid-connected distributed-generation system. Depending on the selected scenario, the electricity generated annually by the solar system may be consumed on-site, exported to the grid, or converted into revenue. Fig. 3 displays the economic analysis, which is calculated according to the parameters corresponding to each scenario. Fig. 3 also highlights the differences and assumptions of each scenario.

In the first scenario, a 110 kW Perkins generator is compared to a 70 kW solar parking lot. In this case, the lifespan of both systems is 20 years. All values indicate expenses, and neither of the systems listed generates revenue.

The second scenario is identical to the first in all aspects except systems' lifetime. Here, both systems are assumed to run for 10 years, and other conditions continue to remain following the first example.

The third scenario considers the generator's average lifetime, which is around 10,000 hours. However, this efficiency-preserving lifetime is only achieved when all generator maintenance conditions are ideal. Generator efficiency can be influenced by short-term use as well as environmental factors, including high temperatures. Similarly, many other elements can further lower generator efficiency:

- Poor quality of the lubricant.

- The low thermal value of the fuel.

- Malfunctions in the performance of the engine and associated components.

- Issues in cooling systems, e.g., aftercoolers and intercoolers.

The lifespan for each condition set lowers a diesel generator's lifetime to 0.5 times from the ideal state. In this case scenario, the diesel generator is substituted after ten years. The other variables as in the previous scenario do not change such as the interest rate, lifetime of the solar parking lot, and solar parking lot capacity. The fourth scenario has the potential for monetization. According to the Ministry of Energy's announcement regarding the construction of solar power plants, government organizations should source 20% of their service lines (contract power) from solar power plants. The electricity contract power for the studied site is 158 kW, with 20% of that amount equaling 32 kW. As previously stated, the total capacity is estimated to be 70 kW. We can determine the sellable produced capacity by subtracting 32 kW from this total, which means we can sell 38 kW of the generated power from this solar parking lot to the distribution company at the guaranteed purchase price. Table 3 displays the results of the simulation for the 38 kW solar parking lot (Scenario 4).

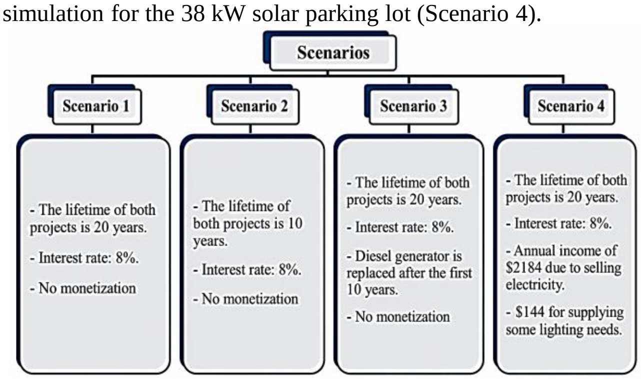

Fig. 3. Assumptions of every scenario.

Table 3. Simulation results of 38kW solar power plant.

Month	Panel-generated electricity (MWh)	Network-injected electricity (MWh)	Performance ratio
January	4.798	4.714	0.922
February	5.331	5.240	0.917
March	6.411	6.302	0.891
April	6.896	6.779	0.865
May	7.433	7.306	0.837
Jun	8.741	8.588	0.815
July	8.334	8.184	0.811
August	8.676	8.527	0.814
September	7.751	7.620	0.831
October	6.338	6.233	0.873
November	4.950	4.866	0.902
December	3.971	3.895	0.938
Year	79.63	78.254	0.856

A calculation of annual electricity sales revenue was performed using PVsyst software for design and simulation (Table 3). We can determine the yearly electricity sales by subtracting the power generated for internal use in June, July, and August from the annual power output of the solar parking facility. The power value is calculated based on the following formula:

$$78.254-(8.588+8.184++8.527)=52.955MWH \quad (4)$$

The Ministry of Energy has declared \$0.04125 as the fixed purchase cost of solar power per kWh for 100 kW power plants under its 2022 purchasing program. The total annual revenue derived from power sales for solar parking lots is \$2,184 per year based on this formula:

$$52.955\frac{MWh}{Year}\times 0.04125\$=2,184\frac{\$}{Year} \quad (5)$$

However, except for the aforementioned months, the solar system provides the necessary lighting for the university areas. Table 4 shows the areas as well as the power requirements for each.

Table 4. Required power of workshop areas.

Area name	Lighting-needed power (W)
Football field	800
Auto-mechanics workshop	460
Laboratory of material strength/vibrations	400
Casting workshop	600
General/machine tools workshop	470
Fluids workshop	1050
Construction workshop	1050
Polymer workshop	800
Lighting of workshop surroundings	200
Sum	5.830

The required electricity for illumination is estimated to be 6 kW. It is anticipated that the aforementioned locations will require lighting for 6 hours per day, 250 days per year. It is worth noting that the solar system does not provide illumination for these locations during June, July, and August. Additionally, the football field projectors are operated for a total of 100 hours per year. The workshops and football field are lit during shoulder and peak hours, respectively. During shoulder and peak hours, the advertised price per kWh of power is \$0.018125 and \$0.03625, respectively.

$$\begin{aligned}
&250\frac{Day}{Year}\times 6\frac{hour}{Day}\times 5.2KW=7800\frac{KWh}{year}\\
&7800\frac{KWh}{year}\times 0.018125\frac{\$}{KWh}=141\frac{\$}{Year}\\
&100\frac{hour}{Year}\times 0.8KW=80\frac{KWh}{Year}\\
&80\frac{KWh}{Year}\times 0.03625\frac{\$}{KWh}\approx 3\frac{\$}{Year}\\
&\Rightarrow 141+3=144\frac{\$}{Year}
\end{aligned} \quad (6)$$

Both projects are expected to last 20 years, with the diesel generator operating under the same conditions as in the first scenario.

4. Results and Discussion

4.1. Scenarios 1 and 2

The economic analysis results for Scenarios 1 and 2 are provided in Tables 5 and 6, respectively.

The sole difference between the two scenarios is the system lifetime (20 years for Scenario 1 versus 10 years for Scenario 2). Consequently, the diesel generator in Scenario 2 has a significantly less negative FV—approximately half the magnitude of that in Scenario 1; due to fewer O&M cycles. The results for both scenarios demonstrate that the diesel generator has a less negative FV than the solar parking system and is therefore more economical under the cost-only conditions considered (see Tables 5 and 6).

The negative FV suggests that all costs associated with this option are considered expenses. Furthermore, by the end of the tenth year, the FV of the expenses for the diesel generator approximates half of the costs of the solar parking lot (see Table 6). Fig. 4 illustrates the FV diagram for the lifetime of Scenario 1, while Fig. 5 presents the corresponding diagram for Scenario 2. The FV diagram of the diesel generator is less orderly than that of the solar system (see Figs. 4 and 5). This notable discrepancy in the slopes of the diagrams for both systems can be attributed to the higher Opexs of the generator.

Table 5. The results of the economics of Scenario 1.

	Capex (\$)	Opex (\$)	Lifetime (year)	*FV* (\$) (lifetime end)
Diesel generator	12675	691.125	20	-50261.42
Solar parking lot	51287	56	20	-54336.58

Table 6. The results of the economics of Scenario 2.

	Capex (\$)	Opex (\$)	Lifetime (year)	*FV* (\$) (lifetime end)
Diesel generator	12675	691.125	10	-26789.81
Solar parking lot	51287	56	10	-52434.74

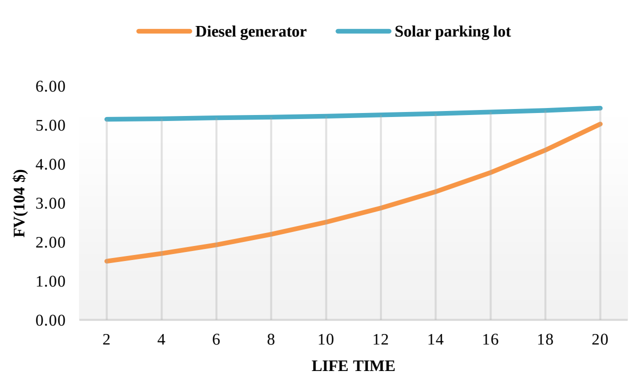

Fig. 4. FVs of diesel generator and solar parking in Scenario 1.

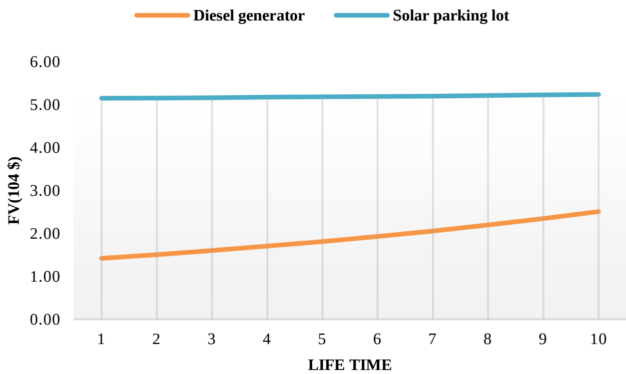

Fig. 5. FVs of diesel generator and solar parking in Scenario 2.

4.2. Scenario 3

Table 7 displays the economic results from the evaluation of Scenario 3. In this scenario, the future value of the diesel generator declines sharply following its replacement in the tenth year. Fig. 6 depicts the FV of Scenario 3 over its entire lifetime. Due to the replacement, the FV diagram of the diesel generator is less clear. The FV schematics of the diesel generator and solar system intersect in the 11th year of the project's life. This point is known as the break-even point.

4.3. Scenario 4

Table 8 shows the financial study data for Scenario 4. The FV matrix of the fourth case is shown in Fig. 7. The results show that the solar parking lot requires a higher upfront cost compared to diesel generators (Capex) and incurs a lower ongoing cost over the years of operation (Opex); consequently, it has a better FV than diesel generators over the 20 years of operation. This point indicates that solar parking lots provide a more promising financial and economic energy-generating alternative. The break-even threshold occurs in the eighth year, as illustrated in Fig.7.

Table 7. The results of the economics of Scenarios 3.

	Capex ($)	Opex ($)	Lifetime (year)	*FV* ($) (lifetime end)
Diesel generator	12675	691.125	2 × 10	-72228.08
Solar parking lot	51287	56	20	-54336.58

Table 8. The results of the economics of Scenario 4.

	Capex ($)	Opex ($)	Lifetime (year)	*FV* ($) (lifetime end)
Diesel generator	12675	691.125	20	-50261.42
Solar parking lot	51287	56	20	63273.88

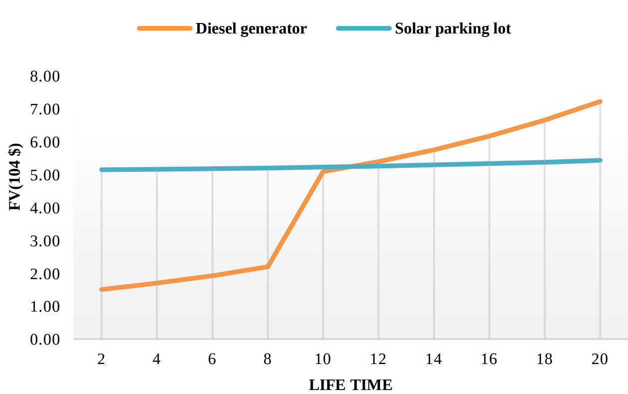

Fig. 6. FVs of diesel generator and solar parking in Scenario 3.

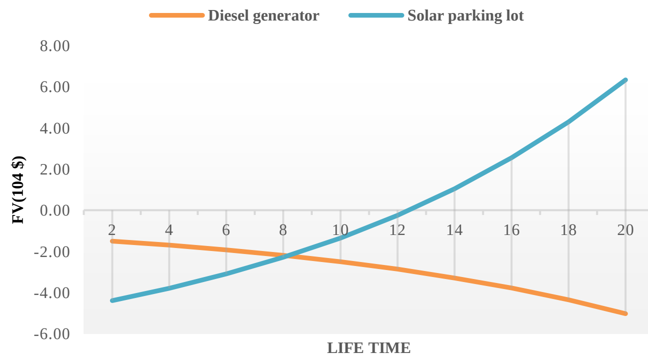

Fig. 7. FVs of diesel generator and solar parking in Scenario 4.

4.4. Comparing different scenarios

Estimations from Scenarios 1 and 2 indicate that employing a diesel generator could be cheaper due to its reduced operational duration. Many studies on solar systems demonstrate economic feasibility because the construction costs of solar power plants exceed those of diesel generators, while the operating expenses for diesel generators exceed those of solar power plants. However, one issue worth noting in such comparisons is that the operating hours of the diesel generator are rather low in this study. As a result, the diesel generator has a less negative FV in Scenarios 1 and 2 and is more economical under these cost-only conditions. Due to the diesel generator's Opexs, the FV difference between the two projects at the end of their lifetimes is greater than the difference in the previous scenario. As expected, a higher diesel generator Opex FV leads to a lower project difference and a longer project lifespan. We can almost consider the FV diagram of the solar system to be constant.

In Scenario 3, similar to Scenarios 1 and 2, all inputs are of the spending type, and the project has no income. Therefore, more negative FV values indicate lower economic feasibility. The magnitude of power produced by the solar system is an important factor that is overlooked in Scenario 3. It only makes sense to generate power in this way when there is demand, as doing so increases the generator's operating hours and escalates operational expenses (Opex). The system thus generates electricity only during the assigned hours, not throughout the entire year. On the other hand, the solar system operates continuously, generating electricity. In Scenario 4, some of the excess power lights the workshop areas while being fed into the national grid.

Scenarios 3 and 4 feature break-even points when the FVs of both designs are equal, and the FV of the diesel generator is more curved than that of the solar system. Both the diesel generator and the solar system are valued the most after the project's lifespan. Given the FV of each system, employing the solar system under the described conditions is more economically feasible in scenario 3. This generator was chosen because it is one of the highest certified and most durable. On the contrary, it was presumed the generator underwent servicing and was maintained periodically. Therefore, the chances of the situational likelihood in Scenario 3 occurring are minimized. As noted in scenario 4, the solar parking project generates revenue that financially supports the project compared to the other three scenarios. However, the project's payback does not occur throughout its lifetime because the Capex is for a 70 kW power plant, while only 38 kW of this plant's output is delivered. On the other hand, during the three peak production months, the generated electricity is consumed for internal purposes, and a considerable volume of annual production is fed into the university's internal grid.

As previously stated, the levelized cost of energy is another factor in establishing a project's economic viability. Smaller values of this metric imply that the project is more cost-effective, as they represent the lowest price per unit of generated electricity. Fig. 8 shows a comparison of the FV for each situation. Under the criteria outlined in Scenario 4, the solar parking lot is the only design with a positive FV and, consequently, economic feasibility.

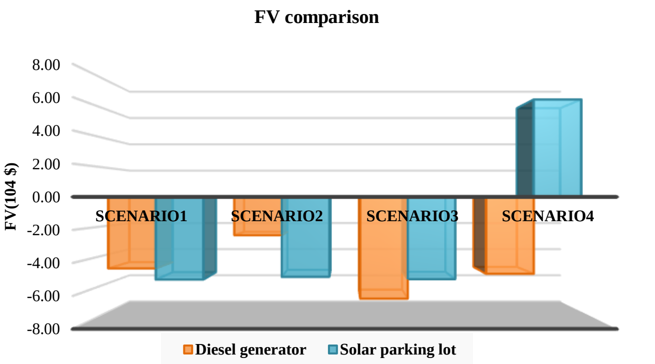

Fig. 8. FVs of diesel generator and solar parking in every scenario.

Table 9. Input and output parameters for each system across every scenario.

Input parameters					
S		*IR* (%)	*IC* ($)	Opex ($/year)	*LF* (Year)
S1	D	8	12675	691.13	20
	SP	8	51287	56	20
S2	D	8	12675	691.13	10
	SP	8	51287	56	10
S3	D	8	12675	691.13	2 × 10
	SP	8	51287	56	20
S4	D	8	12675	691.13	20
	SP	8	51287	56	20
Output parameters					
S		*FV* ($)	*LCOE* ($)	*AGE* (MWh)	
S1	D	-50261.42	0.094	21.12	
	SP	-54336.58	0.044	120.35	
S2	D	-26789.81	0.1284	21.12	
	SP	-52434.74	0.067	120.35	
S3	D	-72228.08	0.1664	21.12	
	SP	-54336.58	0.044	120.35	
S4	D	-50261.42	0.094	21.12	
	SP	63273.88	0.0243	120.35	

S: Scenario; *D*: Diesel generator; *SP*: Solar parking; *AGE*: Annually generated electricity; *LCOE*: Levelized cost of energy; *IC*: Initial costs; *IR*: Interest rate; *LF*: Lifetime

Table 9 compiles all input and output parameters for each system in every scenario. The table also shows the annual electricity output and the levelized cost of energy. Importantly, Scenario 4's solar parking model has the lowest levelized cost. In general, since the solar parking project has a very large annual electricity generation capacity, it consistently maintains a low levelized cost of energy across all scenarios.

The results indicate that the selection of the preferred alternative depends on the operating requirements and economic conditions of the project. The diesel generator may be considered a suitable option when backup power is required only for short periods, diesel fuel is subsidized, the available initial budget is limited, the electricity generated by the PV system cannot be sold or economically consumed, and battery storage is not included. Under these conditions, the diesel generator offers two principal advantages: a lower initial investment and dispatchable operation. It can therefore supply the required load whenever backup power is needed.

In the present study, the diesel fuel price is assumed to be 0.015 $/L, representing a highly subsidized price. Based on the fuel consumption and annual electricity generation of the diesel generator, its fuel-consumption intensity is approximately 0.243 L/kWh. Accordingly, the fuel component of diesel-generated electricity is only about 0.0036 $/kWh. This low fuel cost is one of the main reasons why the diesel generator remains economically competitive in short-duration backup applications

However, the economic result changes considerably when higher diesel prices are considered. For example, the average U.S. retail price of on-highway diesel was reported as 4.578 $/gal on July 6, 2026, which is equivalent to approximately 1.209 $/L[24]. At this price, the fuel component alone would increase to approximately 0.294 $/kWh. This value does not include the initial investment, maintenance, lubricant, labor, or equipment-replacement costs. Therefore, the apparent economic advantage of the diesel generator in the base case is strongly dependent on the subsidized fuel price considered in the analysis.

A similar effect can be observed in several Asian markets, where diesel prices are considerably higher than the price assumed in the present study. Selected retail prices are approximately 0.813 $/L in Vietnam, 0.896 $/L in Taiwan, and 0.981 $/L in Japan[25]. Based on the fuel-consumption intensity of the selected generator, these prices correspond to fuel-cost components of approximately 0.198, 0.218, and 0.238 $/kWh, respectively. Although retail fuel prices may not exactly represent the purchasing conditions of an institutional diesel generator, they provide a useful indication of the sensitivity of diesel-generated electricity costs to local fuel prices and subsidy policies. Therefore, the economic attractiveness of the diesel generator decreases in countries where diesel fuel is more expensive or is not subsidized. The economic value assigned to PV electricity is another important factor affecting the comparison. In the revenue-based scenario of the present study, surplus electricity generated by the solar parking system is sold to the grid, while part of the generated electricity is used to supply the lighting demand. The selling price considered in the analysis is 0.04125 $/kWh.

For comparison, Taiwan's 2025 feed-in tariff for solar PV systems with capacities of 50 kW and above but below 100 kW was approximately 0.131 $/kWh during the first half of the year and 0.130 $/kWh during the second half[26]. These values are more than three times higher than the selling price assumed in the present study. Therefore, the economic performance of the solar parking system improves when the generated electricity can be sold at a more favorable tariff or consumed on-site to reduce electricity-purchasing costs. Overall, the diesel generator is more suitable for short-duration backup applications when fuel is inexpensive, the initial project budget is limited, and battery storage is not considered. In contrast, the solar parking system becomes more attractive when the generated electricity can be sold or consumed internally, diesel fuel prices increase, generator operating hours become longer, favorable financing conditions are available, generator replacement is included in the economic analysis, or environmental benefits are taken into account.

4.5. Normalized Performance Boundary and Backup-Reliability Assessment

To account more explicitly for the different operating profiles of the diesel generator and the solar parking system, a supplementary normalized comparison was also performed based on cost per usable kilowatt-hour, together with fuel-consumption and backup-reliability indicators. Unlike the main case-study scenarios, this comparison does not consider the broader monetization boundary. Instead, it evaluates the two alternatives on the basis of approximately equal annual useful electricity generation.

Under the assumed operating schedule, the diesel generator produces 21.12 MWh/year. A supplementary PV simulation indicated that a 13 kW system could generate approximately 21.5 MWh/year, which is close to the annual electricity supplied by the diesel generator. Therefore, the 13 kW PV system was selected as the equal-energy reference case.

The economic assumptions adopted in the main analysis were also applied to this supplementary comparison. The interest rate and project lifetime were maintained at 8% and 20 years, respectively, resulting in a capital recovery factor of approximately 0.10185. Based on proportional cost scaling from the 70 kW solar parking system, the estimated initial cost of the 13 kW PV system is approximately \$9,500, while its annual Opex is estimated at \$10.4/year. The annualized cost of the system is therefore calculated as follows:

$$C_{\text{annual,PV}} = 9,500 \times 0.10185 + 10.4 \approx 978 \text{ \$/year} \tag{7}$$

Given an annual electricity generation of approximately 21,500 kWh, the normalized cost of the PV system is:

$$C_{\text{PV}} = \frac{978}{21,500} \approx 0.046 \text{ \$/kWh} \tag{8}$$

For the diesel generator, the initial investment is \$12,675, the annual Opex is \$691.13/year, and the annual electricity generation is 21,120 kWh. Its annualized cost is therefore:

$$C_{\text{annual,diesel}} = 12,675 \times 0.10185 + 691.13 \approx 1,982 \text{ \$/year} \tag{9}$$

Accordingly, the normalized cost of electricity generated by the diesel system is:

$$C_{\text{diesel}} = \frac{1,982}{21,120} \approx 0.094 \text{ \$/kWh} \tag{10}$$

The results of the equal-energy comparison are summarized in Table 10.

Table 10. Normalized equal-energy comparison per usable kWh.

Indicator	Diesel generator	13 kW PV system
Annual useful electricity	21.12 MWh/year	21.5 MWh/year
System capacity	110 kW	13 kW
Estimated initial cost	\$12,675	≈ \$9,500
Annual Opex	\$691.13/year	≈ \$10.4/year
Annualized cost	≈ \$1,982/year	≈ \$978/year
Normalized cost	0.094 \$/kWh	0.046 \$/kWh
Fuel-consumption intensity	0.243 L/kWh	0

Although this normalized comparison provides clearer economic and environmental indicators, equal annual energy generation does not imply equivalent backup reliability. The diesel generator is dispatchable and can supply electricity when required. In contrast, PV generation is intermittent, variable, and dependent on solar irradiance. Therefore, replacing the diesel generator as a firm backup source would require the addition of battery energy storage.

Based on the diesel generator's annual output of 21.12 MWh and an assumed annual operating time of approximately 300 h, the average backup load is calculated as:

$$P_{\text{backup}} = \frac{21.12 \text{ MWh/year}}{300 \text{ h/year}} = 70.4 \text{ kW} \tag{11}$$

For a three-hour critical period, the required usable backup energy is:

$$E_{\text{usable}} = 70.4 \text{ kW} \times 3 \text{ h} = 211.2 \text{ kWh} \tag{12}$$

For a preliminary and conservative estimate, an allowable depth of discharge of 80%, an overall storage-efficiency factor of 85%, and a reliability margin of 10% were considered. The required nominal battery capacity is therefore:

$$E_{\text{nominal}} = \frac{211.2}{0.80 \times 0.85} \times 1.10 \approx 342 \text{ kWh} \tag{13}$$

Accordingly, a practical PV-based firm-backup configuration would require a battery energy storage system with a nominal capacity of approximately 340–350 kWh and a power rating of about 75kW.

The NREL 2025 battery-storage cost update reports a 2024 starting-point cost of 334 \$/kWh for a complete four-hour utility-scale lithium-ion battery system [27]. This value represents the overnight capital cost of the complete system. The same report adopts a 15-year lifetime and an 85% round-trip efficiency for its representative four-hour system [28]. Thus, the battery investment would be approximately \$114,000–117,000 in 2024 U.S. dollars. Because the NREL benchmark represents a U.S. utility-scale system, this estimate should be interpreted as a screening-level indicator rather than a site-specific quotation for Qom University of Technology. Furthermore, because the assumed battery lifetime is shorter than the 20-year project period, battery augmentation or replacement should be considered in a complete life-cycle analysis. The results indicate that PV is economically and environmentally favorable when evaluated as a grid-connected distributed-generation system under the equal-energy boundary. However, a PV-only system cannot be regarded as operationally equivalent to a dispatchable diesel backup system. Firm backup capability would require battery storage or another hybrid configuration capable of supplying the critical load during periods of insufficient solar generation.

4.6. Effect of CO_2

Carbon Dioxide (CO_2) is a greenhouse gas that, in ordinary concentrations, has no detrimental effects on the atmosphere but acts as a blanket, preventing the earth's heat from escaping into space. However, the increasing concentration of this greenhouse gas has attracted considerable attention in recent years due to its correlation with global warming. The unmistakable trend of global warming is directly responsible for the rising rate of natural calamities such as floods and droughts[29]. As a result, all human activities strive to reduce CO_2 emissions. In this regard, energy economics has been established to minimize the amount of pollutants produced by energy generation[30]. This section investigates the annual CO_2 emissions produced by each system. The method outlined below is used to calculate the amount of CO_2 emitted by diesel fuel combustion. The following describes the chemical equation for diesel fuel combustion:

$$C_{13}H_{28} + 20O_2 \rightarrow 13CO_2 + 14H_2Oa \tag{14}$$

According to the equation above, 13 mol of CO_2 is produced per mole of diesel fuel burned. Diesel fuel has a molar mass of 184.37 g/mol, while CO_2 has a molar mass of 44.01 g/mol. Each liter of diesel fuel weighs 0.850 kg:

$$\begin{aligned}
&1mol\ \ diesel\ fuel \rightarrow 184.37\frac{g}{mol}diesel\ fuel \\
&\xrightarrow{850g} 4.61mol\ \ diesel\ fuel \\
&4.61 \times 13 = 59.93molCO_2 \\
&59.93molCO_2 \times 44.01\frac{g}{mol}CO_2 = 2,637.69gCO_2
\end{aligned} \tag{15}$$

The burning of one liter of diesel fuel results in the emission of

2.637 kg of carbon dioxide into the environment. The diesel generator uses 17.1 liters of diesel fuel per hour. The generator provides electricity for 300 hours per year. As a result, the project requires 5,130 liters of this fuel every year. Table 11 compares the CO_2 emissions from the diesel generator with those avoided by the solar system.

A yearly output of 21 MWh of electricity produced by the diesel generator will lead to extensive CO_2 emissions. The more the generator is operated, the greater the emission of pollutants. Renewable electricity generation can significantly reduce operational CO_2 emissions compared with electricity produced from fossil fuels. This solar system generates 120 MWh of electricity per year (Table 9). If powered by fossil fuels, this figure would emit a significant amount of CO_2 into the atmosphere. The volume of CO_2 saved from entering the environment is estimated by creating this solar parking lot using the PV*SOL software. This design has prevented the emission of 56,564 kg of CO_2 into the atmosphere (Table 11).

In Fig. 9, the positive values indicate the cumulative direct CO_2 emissions produced by the diesel generator, whereas the negative values for the solar parking system represent cumulative avoided emissions rather than actual negative emissions

Table 11. Comparison of CO_2 emissions between a diesel generator and a solar system.

	Operation years of generator	CO_2 (kg)
D	1	13,531[a]
	10	135,313
	20	270,627
SP	1	56,564 [b]
	10	565,640
	20	1,131,280

[a] CO_2 emissions, [b] Prevented CO_2 emissions.

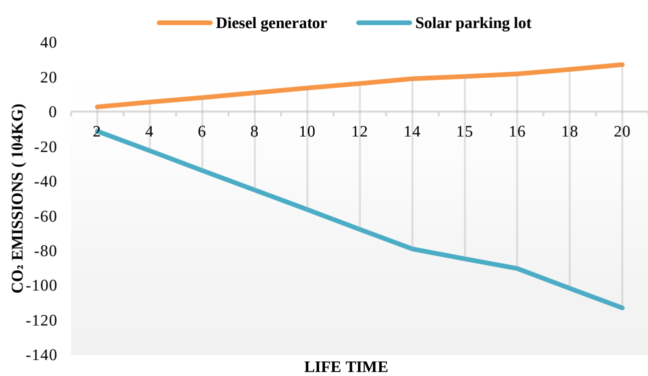

Fig. 9. Cumulative direct CO_2 emissions from the diesel generator and avoided CO_2 emissions associated with the solar parking system.

5. Future Studies

Future research should build on the present case study by adopting a time-resolved approach based on measured campus load profiles, documented outage events, and actual system operating data. This would allow a more accurate assessment of the temporal alignment among solar electricity generation, campus demand, and backup-power requirements. The current grid-connected configuration could also be extended to include battery energy storage or a hybrid PV–diesel–battery system. In such configurations, system capacity and operating strategy should be optimized simultaneously with respect to cost, reliability, and CO_2-emission reduction. Reliability metrics, including unmet load and loss-of-load probability, should therefore be evaluated alongside conventional economic indicators. Further research should also examine the effects of uncertainty in diesel-fuel prices, electricity purchase tariffs, interest rates, PV degradation rates, and equipment-replacement costs through sensitivity analysis or probabilistic methods. Finally, applying the proposed framework to other universities and institutional facilities across different climatic and economic contexts would help assess the transferability of the methodology and the broader applicability of the findings.

6. Conclusions

The four scenarios represent a progression from purely cost-driven decisions (Scenarios 1 and 2) to replacement risk (Scenario 3) and finally to revenue maximization (Scenario 4). This framework provides an integrated decision-making approach for different stakeholders under varying policy and operational conditions. The assessment of two solar-powered parking lot systems, alongside the diesel generator, produced results that focused on carbon dioxide emission measurements:

- Although the diesel generator is more economical in Scenarios 1 and 2 because of its lower initial cost and limited operating period, the need for generator replacement in Scenario 3 and the monetization of solar electricity in Scenario 4 make the solar parking system the more economically attractive option.
- Longer lifetimes cause the FVs between the solar parking lot and the generator to progressively converge, so generating a break-even point. For instance, in Scenario 3 this point arises in the 11th year, whereas in Scenario 4 it occurs as early as the 8th year.
- By monetizing the solar parking lot project, its financial viability is much enhanced. In Scenario 4, the solar system not only meets internal power needs but also makes extra money by selling surplus electricity to the grid, so producing a positive FV of $63,273.88 over 20 years.
- The solar system consistently generates more electricity (120 MWh annually) than the diesel generator (21 MWh annually), resulting in a lower levelized cost of energy ($0.0243/kWh for solar compared to $0.094/kWh for diesel in Scenario 4).
- Although the diesel generator produces 13,531 kg of CO_2 yearly, the solar system has major environmental benefits since it helps to stop the yearly emission of 56,564 kg of CO_2. The avoidance of 1,131,280 kg of CO_2 emissions over 20 years shows the vital part the solar system plays in slowing down global warming.

Under the assumptions of Scenario 4, the solar parking system is the preferred option for the study site, as it combines electricity monetization with a lower LCOE and substantial reductions in CO_2 emissions. However, the relative attractiveness of the two alternatives remains sensitive to fuel prices, electricity tariffs, financing conditions, operating hours, and backup-power reliability requirements.

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