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*Research Article*

# Investigating the Cost-Effectiveness of Solar Electricity Compared to Grid Electricity in the Capitals of Middle Eastern Countries: A Residential Scale Case Study

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Despite of being rich in fossil fuels, the Middle East is currently the main energy consumer and is projected to have the highest growth in energy demand in the world. Due to its great potential in the Middle East, solar energy can play an important role in the plans of energy decision-makers in the region. According to the studies done so far, no study has been done to show the potential benefit of using home-scale solar systems in the Middle East. Therefore, in this work for the first time, the potential of solar electricity production in the capitals of Middle Eastern countries has been studied using HOMER V2.81 software. The investigations are technical, economic, energy, and environmental, and the studied solar system is connected to the national electricity grid. The results showed that in Nicosia, due to the sale of electricity to the grid, the levelized cost of electricity (LCOE) is equal to -0.759 $, which is the lowest price for produced electricity and leads to a return on investment time of 5.69 years for this system. The solar fraction for the Nicosia station is 92%, which prevents the emission of more than 8 tons of $CO_2$ pollutants during the year. The highest value of LCOE with the amount of $0.25 is related to Sana'a, whose investment return time, solar fraction, and annual $CO_2$ emission prevention amount are 14.1 years, 53%, and 1162 kg, respectively. Ranking analysis was done on the results of 5 outputs of the HOMER software as well as 3 other influential parameters using 4 multicriteria decision-making (MCDM) methods. TOPSIS, GRA, WSM, and AHP methods were used, and the final ranking of each station was considered the average of the 4 methods. According to the results, Cyprus and Kuwait stations were the best and worst, respectively.

## 1. Introduction

The Middle East and North Africa (MENA) region has the most energy resources among the developed and developing regions and is the third largest emitter of $CO_2$ in the world. However, energy demand still exceeds its production, which is estimated to triple by 2030 [1]. Despite its position and reputation as a region dominated by oil states, the Middle East is making plans for renewable energy efficiency [2].

The solar energy system constitutes more than 45% of the total capacity of sustainable energy systems in 2050 and is considered the most comprehensive renewable energy system [3]. Solar photovoltaic (PV) is one of the most reliable, efficient, and fast technologies for supplying electricity in the world, and the decrease in the price of PV modules motivated the use of this technology [4]. Since solar energy is the most abundant form of renewable energy, the use of solar technologies can significantly reduce concerns related to energy security, climate change, unemployment, etc. [5].

In 2021, with the addition of 175 GW of solar energy, the total global capacity reached 942 GW, which maintained its increasing trend compared to previous years (Figure 1) [6]. This increasing trend shows the global desire to use more solar energy, which is another reason for doing the present work for the first time in the Middle East.

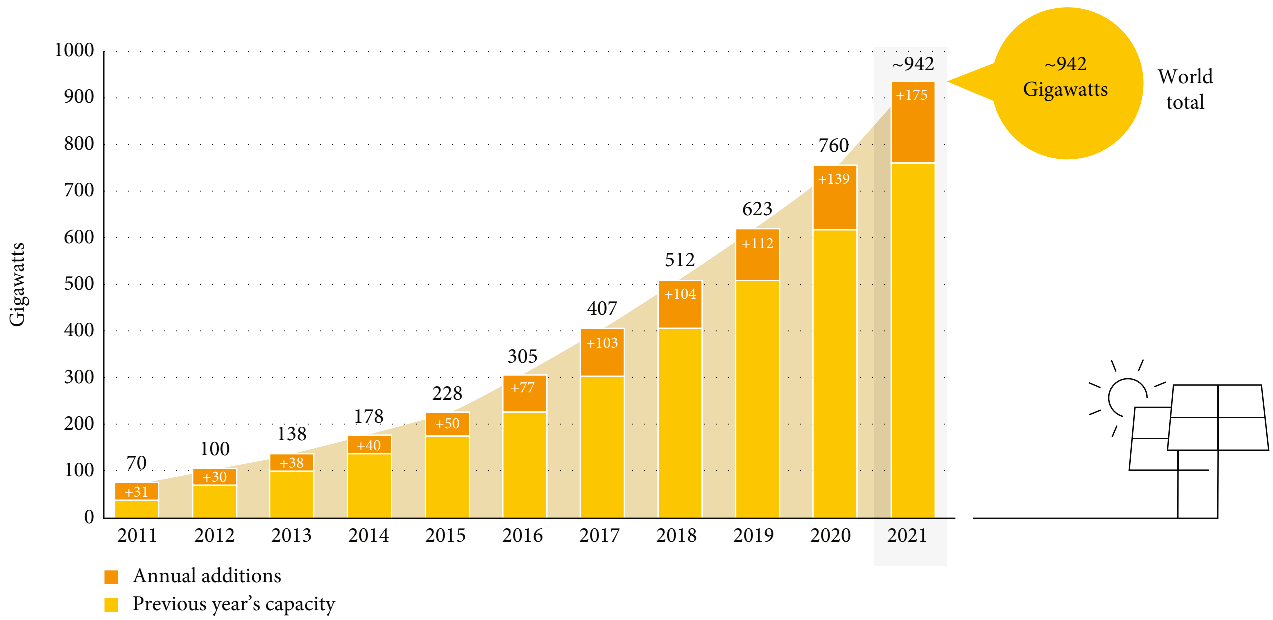


Figure 1: PV global capacity from 2011 to 2021 [6].

It is estimated that the world's electrical energy needs will reach 40,000 TWh in 2050, of which renewable energy supplies more than 16,000 GW [3]. Solar energy can be used by the decentralized installation of solar panels on the roof of buildings for social and domestic purposes [7]. In addition to advantages such as clean energy production, low maintenance cost, simple and noiseless process, and high energy production in summer afternoons, the initial investment in this method is usually kept high [8].

In the past years, many scattered studies have been conducted regarding the efficiency of solar energy in Middle East countries, and a number of them are reviewed in Table 1. The present work has investigated the costs of using small-scale solar systems for home use in the capital of each country by using the HOMER software and using geographical data. Because solar energy is easy to implement and produces very low noise in residential areas compared to other renewable energies. Usually, the capital cities need more energy than the rest of the country due to the large number of residents they have. In the following, the total revenue of the system and sales to the grid, if the system is profitable and the return on initial investment time, are discussed.

## 2. The Solar Situation in the Middle East Countries

Bahrain has one of the best solar radiation positions in the world. The total energy production capacity of this country is 4 GW, which is all dependent on natural gas. In the next 10 to 15 years, this country should more than double its current energy production capacity because it is estimated that the peak energy demand will reach 9.5 GW by 2030 [9].

In Cyprus, almost all the energy needed is from fossil fuels, and a small amount is obtained from solar energy. Due to its dependence on oil imports, it is highly vulnerable to oil shocks and faces a lack of energy security. Despite these cases, Cyprus requires the creation of strategic alternative sources such as solar energy [24].

Egypt plans to meet 42% of its energy needs with renewable energy by 2035. Egypt has a lot of solar radiation. Egypt has implemented incentive policies in the field of implementing and using small-scale PV systems to encourage people, which can be referred to as an annual increase in the retail price of electricity. Until 2020, the total capacity of PV installed in this country is about 300 MW [25].

In Iran, most of the electricity production units use fossil fuels because this country has the second-largest natural gas reserves and the fourth-largest oil reserves in the world. Since the energy demand in Iran has increased by 5% annually in the last 10 years, Iran must think of new sources to meet its needs that have lower greenhouse gas emissions and indirect costs. On average, Iran has about 2900 hours of sunshine per year, and if only 1% of Iran's area is covered with solar cells, the energy obtained is 5 times the country's annual gross electricity production [26].

Iraq has faced energy shortages since 1991, after extensive destruction, even with vast resources of fossil fuels. The presence of rich fossil sources in Iraq has made officials in the country not interested in using solar energy. Even in deserts with proper solar radiation (about 31% of Iraq's land), the importance of using solar energy is not recognized among the people and the government. However, the use of renewable energy in this country is necessary to solve the energy shortage [27].

Jordan is facing two problems: energy demand growth due to economic growth and the influx of refugees from neighboring countries and a lack of internal resources. Therefore, it has provided suitable conditions for the adoption of renewable technologies [28]. In 2018, imported fossil fuels supplied 86%, domestic sources 7%, and renewable energy 7% of Jordan's energy. Jordan has about 310 sunny days per year with an average daily solar radiation of about

Table 1: Previous studies conducted in the study area.

| Year [Reference] | Country | Subject | Result | Exchange with grid | Total cost/revenue estimation | Homemade scale | Focusing on the capital of country |
|---|---|---|---|---|---|---|---|
| 2018 [9] | Bahrain | The potential of building a 1 MW solar PV farm | The production cost of each kW of produced electricity will be 43% lower than the current cost. | Yes | Yes | No | No |
| 2021 [10] | Cyprus | Investigating the potential of solar electricity in Near East University Hospital | The area has a high solar potential, and the production cost per kW is between \$0.0187 and \$0.0389. | No | Yes | No | No |
| 2019 [11] | Egypt | Investigating the wind-solar hybrid system connected to the power grid | The best scenario consists of PV and WT, where the cost of producing each kW of electricity is estimated at \$0.026. | Yes | Yes | Yes | No |
| 2018 [12] | Iran | Investigating the best area to install small-scale solar PV | Southern cities of Iran are more suitable for systems below 10 kW. | No | Yes | Yes | No |
| 2020 [13] | Iraq | A case study on solar power system | Due to the connection of only a few hours of national electricity for most people, home solar power will be a good solution. | No | Yes | Yes | No |
| 2018 [14] | Jordan | Investigating the solar-wind hybrid system for a cement factory | The solar-wind hybrid system will have the highest efficiency with a production cost of \$0.203 per kW. | No | Yes | No | No |
| 2016 [15] | Kuwait | Investigating the possibility of supplying electricity to the house by means of panels installed on their roofs | The cost of electricity produced is about \$0.078 per kW and less than half of the cost of electricity produced by a generator. | Yes | Yes | Yes | No |
| 2020 [16] | Lebanon | Assessment of wind and solar energy potential in the Riyaq region | The production cost of each kW of solar electricity of a 100 MW farm is \$0.085, and the total investment return time of the project is 13.5 years. | No | Yes | No | No |
| 2019 [17] | Oman | Choosing the best area for solar energy | The cost of producing each kW of solar electricity in this farm with a capacity of 1164 KVA will be equal to \$0.0763 in the city of marmol, the best scenario. | No | Yes | No | No |
| 2020 [18] | Qatar | Finding the best area to exploit wind-solar energy for hydrogen and electricity production with a fuzzy multicriteria technique | From the point of view of MCDM and the fuzzy technique for order performance by similarity to ideal solution (FTOPSIS) technique, the best point for using combined wind-solar energy for hydrogen production is the Doha International Airport site. | Yes | Yes | Yes | No |
| 2017 [19] | Saudi Arabia | Investigation of a small-scale solar farm | The production cost per kWh in the best scenario from the point of view of return on investment will be \$0.08 for a solar system with a capacity of 12 kW. | Yes | Yes | Yes | No |

Table 1: Continued.

| Year [Reference] | Country | Subject | Result | Exchange with grid | Total cost/revenue estimation | Homemade scale | Focusing on the capital of country |
|---|---|---|---|---|---|---|---|
| 2019 [20] | Syria | Evaluation of the 300 kW solar system from a technical-economic point of view | The electricity produced in this system is calculated at $0.094 per kW, which is cheaper than the price of grid electricity and will bring an 11-year return on investment time. | Yes | Yes | No | No |
| 2018 [21] | Turkey | Analysis of hybrid off-grid xsystem (solar-wind-fuel cell-battery) from a technical-economic point of view | The cost of producing each kWh of electricity in the ideal system is equal to $0.186. | No | Yes | Yes | No |
| 2021 [22] | UAE | A renewable energy system for an off-grid home in the suburbs of the UAE | The cost of producing each kWh of electricity in the hybrid system (solar-fuel cell-diesel generator-battery) will be equal to $0.34; of course, more than 90% of the energy is solar. | No | Yes | Yes | No |
| 2021 [23] | Yemen | Investigating the potential of energy production by the hybrid system for all types of consumers | The proposed scenario is a solar-wind-diesel-battery generator hybrid system, which will cost $0.175 per kWh of electricity. | Yes | Yes | Yes | No |
| Present work, 2022 | Middle East | Finding the best location in the Middle East for using on-grid PV in household-scale | Nicosia with LCOE equal to $-0.759 and 5.60 payback time is the best PV station in the Middle East. | Yes | Yes | Yes | Yes |

5.6 kWh/m$^2$ and total annual radiation between 1800 and 2700 kWh/m$^2$ [29].

In 2014, electricity consumption in Kuwait reached 15,591 kWh, an increase of 19% compared to 1995, which shows the growing demand for energy. Due to the limitations of using fossil fuels, this type of energy does not have the ability to meet the needs of this country. Therefore, solar energy has the potential to help supply the required electricity and provide economic diversification in Kuwait [30].

Lebanon suffers from a severe energy shortage and is unable to provide 24-hour electricity. Currently, diesel generators compensate for some of the lack of energy, which has excess costs. In Lebanon, electricity is supplied by fossil power plants, hydroelectricity, and imports. The production capacity (1500 kWh) only reaches about half of the demand (3000 kWh) and increases the importance of using renewable energy [16]. Lebanon has an average daily solar radiation of about 4.8 kWh/m$^2$, which is considered a good potential for radiation and has a lower environmental impact [31, 32].

In 2018, oil and natural gas accounted for 99.7% of Oman's energy production resources [33], which led to the country being among the 25 countries with the highest greenhouse gas emission rates in the world [34]. Following these events, Oman is experiencing an unprecedented level of environmental degradation [35]. The use of PV systems can reduce the annual rate of air pollutants and increase the energy production cost to \$0.085/kWh [17].

In the years 2010-2020, Qatar had the highest growth rate of energy demand among the countries of the Persian Gulf Cooperation Council [36]. It is the largest exporter of liquefied natural gas in the world and supplies its domestic energy using natural gas (76%) and crude oil (23%). It is predicted that by 2030, renewable energies will meet 20% of Qatar's domestic demand. Qatar has an average of 9.5 hours of sunshine per day [37].

Energy demand in Saudi Arabia reached 10.2 MWh in 2018, which was a 41.7% growth compared to 2006 [38]. The Saudi government is thinking about reducing dependence on oil and diversifying its economy by presenting the "2030 Vision of Saudi Arabia" [39]. In this country, about 80% of the total electricity production is used by buildings, which is much higher than the global average in this area [40], which forces this country to reduce oil exports. The efficiency of solar energy can reduce the use of fossil resources in Saudi Arabia [41].

The start of the war in Syria has had a negative impact on the supply of energy in this country. 96% of the energy produced in 2017 was produced by fossil fuels and the remaining 4% by hydropower plants. Syria has about 300 sunny days a year with adequate solar radiation [42]. The average horizontal solar radiation in Syria is estimated to be about 5 kWh/m$^2$/day, and the use of solar resources contributes to the country's energy independence [43].

Turkey is considered a developing country and faces an annual growth in energy demand [44]. Turkey's domestic reserves of fossil fuels are limited, and Turkey has set its energy policies to reduce this dependence on fuel imports [45]. The installed energy production capacity between 2016 and 2018 was associated with a growth rate of 12.8% [46]. Energy production by PV power plants experienced a growth of nearly 6 times between 2014 and 2018 [47]. Turkey benefits from an average of 7.5 hours of daily radiation [48]. It is predicted that by 2040, Turkey will provide 40 GW of its energy needs by solar energy [49].

The UAE contains about 6% of the world's crude oil reserves and provides 3.8% of the world's oil consumption [50]. Electricity demand has increased by about 9% every year until 2019 [51]. 35% of oil and 65% of natural gas are used in the production of electricity in the UAE [52]. This country has an average of 350 days a year and more than 10 hours of sunshine per day [53]. The UAE has strategies based on the development of productivity from renewable resources; the main of these activities is solar PV projects [54, 55].

Since 2015, with the start of the war in Yemen, this country has faced an energy crisis, and according to the United Nations report, almost 90% of Yemen's population has lost electricity [56]. Lack of energy has caused Yemen to be known as the weakest country in the Middle East in terms of economy, education, trade, and tourism [57]. One of the problems of electricity production in Yemen is dependence on fossil fuels [58]. Nearly 85% of people around Sana'a use solar panels to supply their energy [59]. Yemen has a very good radiation situation, the efficiency of which helps to supply the country's energy deficit [60, 61].

In the tropical countries of Asia and Africa, the abundance of sunny days (about 300 days per year) can be an incentive to use the potential of solar energy [62]. The Middle East has oil-based economies, and governments can diversify the region's economy by using huge residential lands, vast empty deserts, and high solar resources at their disposal [8]. The sustainable energy sector in the future will provide an opportunity for oil-dependent countries to increase and diversify their economic, political, and international power [2]. The energy production capacity of the PV system has a positive correlation with the amount of solar radiation and the duration of solar radiation [63]. Figure 2 shows the 20-year average radiation potential of the Middle East, which is much more intense in the southern part. It can be seen from Figure 2 that the radiation potential in the Middle East is very significant, which shows the necessity of the investigation carried out in the present work.

## 3. Methodology

*3.1. Energy-Economic-Environmental analysis.* The HOMER software, produced by the US National Renewable Energy Laboratory (NREL), has high accuracy in long-term simulations and performs financial, technical, and environmental, energy analyses simultaneously [65]. In addition, it has the possibility of connecting to the national electricity grid of any country, taking into account the electricity tariff of that country. Another important point is that the HOMER software is directly linked to the 25-year average data of the NASA website, so its results are not related to a specific year and are more in line with the reality of the current situation [66].

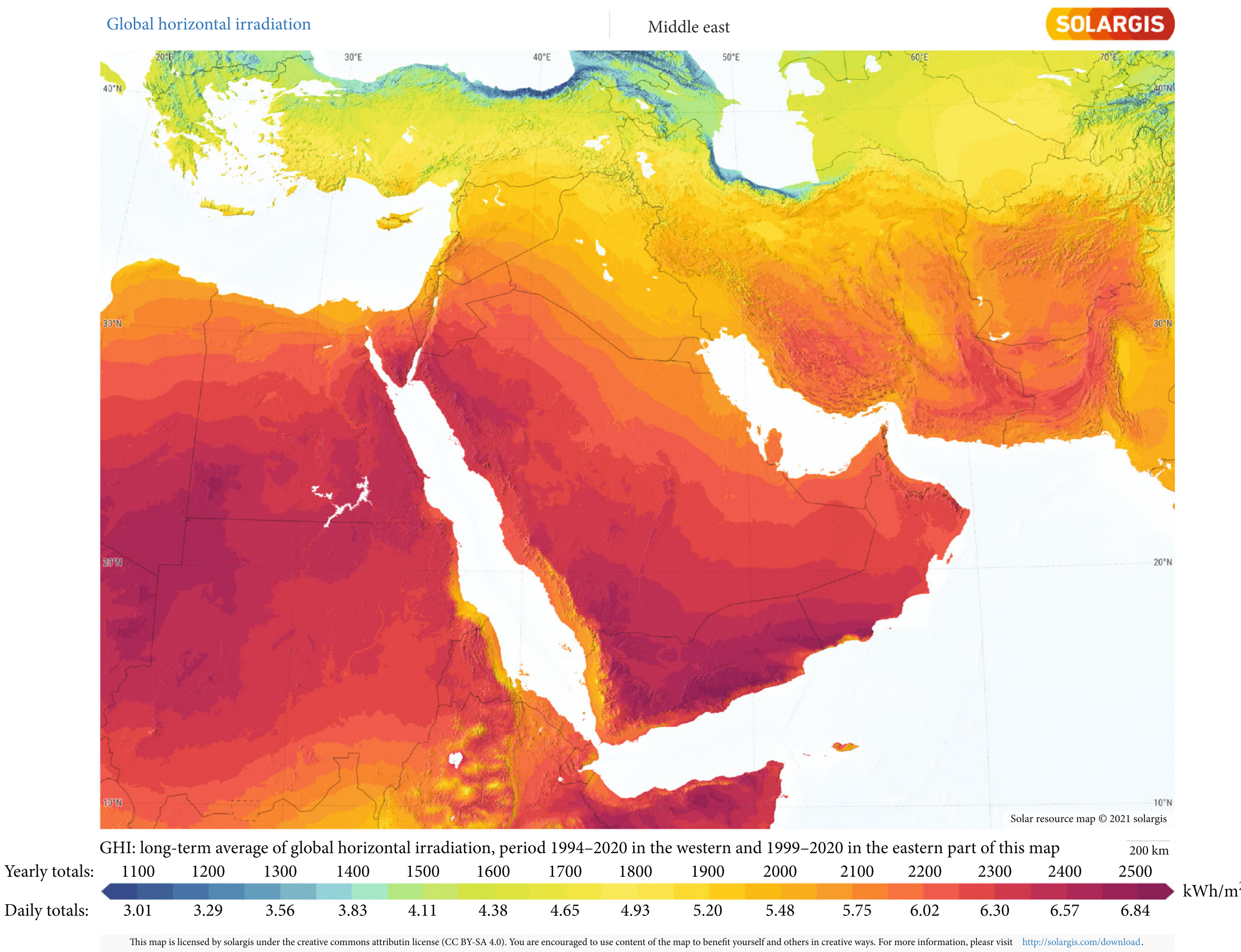


FIGURE 2: The intensity of horizontal solar radiation in the Middle East [64].

Figure 3 shows the flowchart of the simulation performed in the present work. First, based on 20-year average solar radiation data, the simulation is done for the capital of each country. The simulations are such that the amount of electricity required by the residential house is given to the software, and the amount of supply is checked by solar energy. Surplus electricity is sold to the grid based on the tariff of each country, and the amount of return on capital and profit is determined. Finally, the results are ranked based on the lowest to the highest total net present cost (NPC).

HOMER software uses the following equation to calculate photovoltaic output power [67]:

$$P_{PV} = Y_{PV} f_{PV} \left( \frac{\bar{G}_T}{\bar{G}_{T,STC}} \right) [1 + \alpha_P (T_c - T_{c,STC}). \quad (1)$$

In this equation, $Y_{PV}$ is equal to the rated potential of $PV$ which means its output power in standard conditions (kW), $f_{PV}$ is equal to the PV reduction factor (%), $\bar{G}_T$ shows received radiation at the current time (kW/m$^2$), $\bar{G}_{T.STC}$ represents the received radiation in standard test conditions (1 kW/m$^2$), $\alpha_P$ is equal to the power temperature coefficient (%/°C), $T_c$ is the temperature of the PV cell in the current time (°C), and $T_{c,STC}$ is equal to the PV cell temperature in standard test conditions (25°C).

HOMER compares two systems to measure the payback time, which means the number of years that the initial investment cost is returned by the income of the system. In some systems connected to the grid for electricity (such as the present work), the sale of excess electricity to the grid is considered system income, which is included in the calculation of return on investment time [68]. In the present work, the return on investment time of a system means comparing it with the grid electricity of the relative country, and the lack of return on investment time shows that the analyzed system is not cost-effective compared to the cost of using grid electricity.

The converter capacity factor is obtained by dividing the average output by the nominal capacity, which is measured as (%) [69].

The PV capacity factor is obtained by dividing the average output power by the rated power and is expressed as (%) [70].

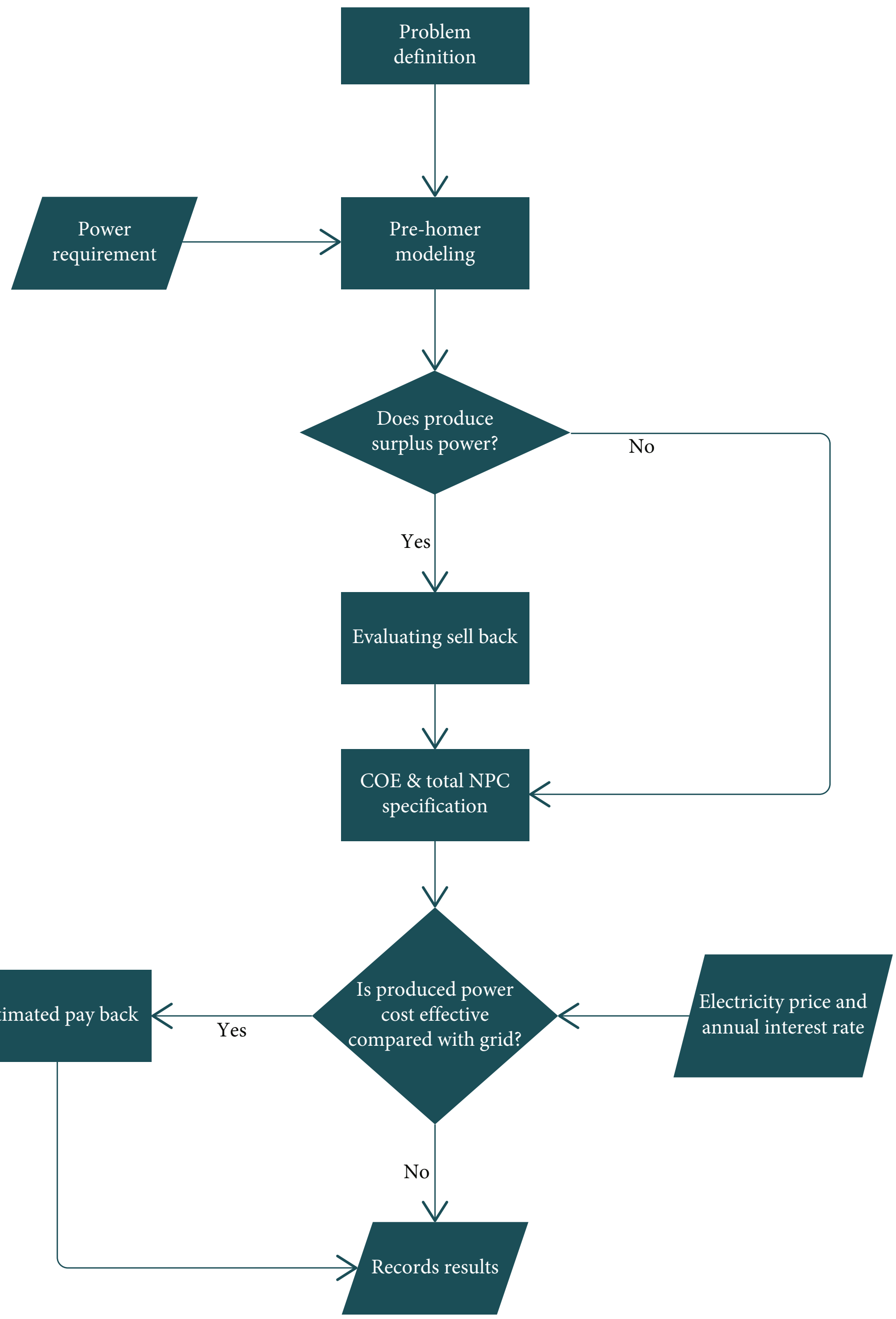


Figure 3: Flowchart of present work simulation.

LCOE in HOMER means the average cost of each (kWh) of energy produced in the system, which is calculated by dividing the total cost of annual electricity production by the electricity consumed [71]

$$LCOE = \frac{C_{ann.tot}}{E_{load\ served}}. \quad (2)$$

In this equation, $C_{ann,tot}$ is the total annual cost of the system ($/yr) and $E_{load\ served}$ is equal to the total electrical load provided (kWh/year). Total annualized cost ($C_{ann,tot}$) is calculated according to the following equation [72]:

$$C_{ann.tot} = CRF\left(i.R_{proj}\right).C_{NPC.tot}. \quad (3)$$

In this equation, $C_{NPC,tot}$ is equal to the total net present cost, $i$ is equal to the real annual discount rate (%), $R_{proj}$ is equal to the life of the project (year), and CRF represents the capital recovery factor.

HOMER software considers the total net present cost equal to the sum of the total discounted cash flows in each year of the project's life [73]. In the HOMER software, the capital recovery factor is calculated from the following equation, where $i$ represents the actual discount rate and $N$ represents the number of years [74].

$$\mathrm{CRF}(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1}. \quad (4)$$

The capacity factor parameter is obtained from the following equation:

$$\text{Capacity factor} = \frac{\text{Average power output}}{\text{Rated power}}. \quad (5)$$

The simulations were done by HOMER software for a period of 25 years and for 15 different stations in 15 different countries. It should be noted that the HOMER software was developed by the NREL, and its results are very valid and with a high percentage of agreement with real and experimental results. Also, this software has been used by researchers all over the world for research and practical work, and its accuracy has been confirmed. According to the scope of the study carried out in the present work, it is practically not possible to investigate it in an experiment. Also, according to the technical, economical, energy, and environmental analyzes performed in the present work, which are the basis for drawing conclusions, it is not possible to use survey data in this regard. In addition, as mentioned in the references [75, 76], for works on this scale of geographic extent and long-term time frame, the only way is to use simulation software to estimate the important parameters of the problem. Of course, provided that the software under review has high accuracy in calculations and its results can be cited.

*3.2. Ranking Analysis.* MCDM methods including TOPSIS, GRA, WSM, and AHP were used to rank the investigated stations. The equations governing the methods are as follows.

*3.2.1. TOPSIS Method [77]*

*Step 1.* Calculate the normalized matrix.

$$\bar{X}_{\mathrm{ij}} = \frac{X_{\mathrm{ij}}}{\sqrt{\sum_{i=1}^{n} X_{\mathrm{ij}}^2}}. \quad (6)$$

*Step 2.* Calculate the weighted normalized matrix.

$$V_{\mathrm{ij}} = \bar{X}_{\mathrm{ij}} \times W_j. \quad (7)$$

*Step 3.* Calculate the ideal best and ideal worst value (minimum and maximum of $V_{\mathrm{ij}}$ as "$V^+$" and "$V^-$" for nonbeneficial criteria; minimum and maximum of $V_{\mathrm{ij}}$ as "$V^-$" and "$V^+$" for beneficial criteria).

*Step 4.* Calculate the Euclidean distance from the ideal best and ideal worst.

$$S_i^+ = \left[\sum_{j=1}^{m}\left(V_{ij} - V_j^+\right)^2\right]^{0.5}, \quad (8)$$

$$S_i^- = \left[\sum_{j=1}^{m}\left(V_{ij} - V_j^-\right)^2\right]^{0.5}. \quad (9)$$

*Step 5.* Calculate the performance score.

$$\mathrm{P_i} = \frac{\mathrm{S_i^-}}{\mathrm{S_i^+} + \mathrm{S_i^-}}. \quad (10)$$

*3.2.2. GRA Method [78]*

*Step 1.* Normalizing the data
for higher the better:

$$x_i^*(\mathrm{k}) = \frac{x_i^0(k) - \min \mathrm{x}_\mathrm{i}^0(k)}{\max x_i^0(k) - \min x_i^0(k)}, \quad (11)$$

for lower the better:

$$x_i^*(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(\mathrm{k}) - \min x_i^0(k)}. \quad (12)$$

*Step 2.* Determining the deviation sequence by using the equation below.

$$x_i^*(k) = 1 - \frac{\left|x_i^0(k) - x_i^0\right|}{\max x_i^0(k) - x_i^0}. \quad (13)$$

*Step 3.* Estimating the Grey relational coefficient via equation below.

$$\zeta_\mathrm{i}(k) = \frac{\Delta_{\min} + \zeta.\Delta_{\max}}{\Delta_{\mathrm{oi}}(\mathrm{k}) + \zeta.\Delta_{\max}}, \quad (14)$$

$$\Delta_{0\mathrm{i}}(k) = |\mathrm{x}_0^*(k) - \mathrm{x}_\mathrm{i}^*(k)|, \quad (15)$$

where $\Delta_{\max}$=1.000, $\Delta_{\min} = 0.000$, and $\zeta = 0.5$.

*Step 4.* Grey relational grading by using the equation below.

$$\gamma_\mathrm{i} = \frac{1}{\mathrm{n}}\sum_{\mathrm{k}=1}^{\mathrm{n}} \omega_\mathrm{k}\zeta_\mathrm{i}(\mathrm{k}), \quad (16)$$

where $\omega_\mathrm{k}$ is the weight of specific criteria and $n$ is the quantity of criteria.

*3.2.3. WSM Method [79]*

*Step 1.* Normalizing the data

Table 2: Random index.

| Attributes | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|
| Random index | 0.52 | 0.89 | 1.11 | 1.25 | 1.35 | 1.4 | 1.45 | 1.49 |

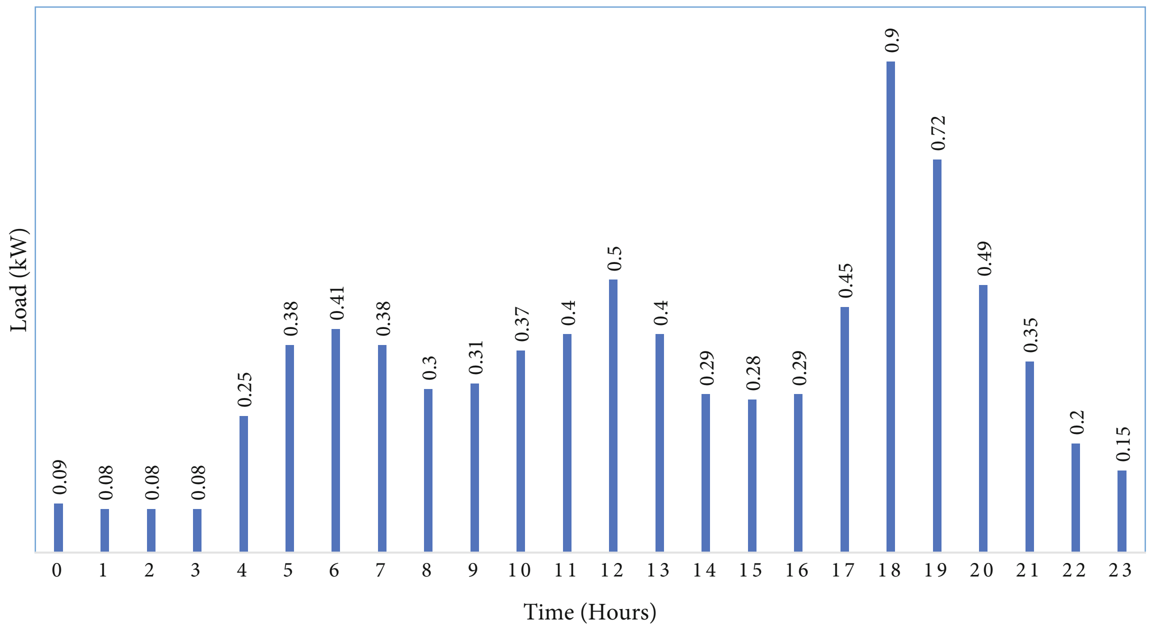


Figure 4: The hourly chart of household consumption.

for beneficial criteria

$$\bar{x}_{ij} = \frac{x_{ij}}{\max_i x_{ij}}, \quad (17)$$

for nonbeneficial criteria

$$\bar{x}_{ij} = \frac{\min_i x_{ij}}{x_{ij}}. \quad (18)$$

*Step 2.* Calculating the total relative importance using the following equation.

$$Q_i^{(1)} = \sum_{j=1}^{n} \bar{x}_{ij} w_j, \quad (19)$$

where $w_j$ is weight of $j^{\text{th}}$ criterion.

*3.2.4. AHP Method [80]*

*Step 1.* Inserting pair-wise comparison weights of criteria in Saaty's matrix.

$$\left(S_{ij}\right) = \frac{w_i}{w_j}, \quad (20)$$

where $w_i$ is weight of $i^{\text{th}}$ criterion.

*Step 2.* Calculating the $S_i$.

$$S_i = \prod_{j=1}^{k} S_{ij}. \quad (21)$$

*Step 3.* Calculating the $v_i$.

$$v_i = \frac{S_i}{\sum_{i=1}^{k} S_i}. \quad (22)$$

*Step 4.* Multiplying step 1 and step 3 into each other.

$$U = \left(S_{ij}\right) \times \left(v_i\right). \quad (23)$$

*Step 5.* Estimating the Consistency index.

$$P_i = \frac{U_i}{v_i}, \quad (24)$$

$$\text{Consistency Index} = \frac{\left(\sum_{i=1}^{k} P_i/n\right) - n}{n-1}, \quad (25)$$

where $n$ is quantity of criteria.

*Step 6.* Calculating the consistency ratio.

$$\text{Consistency Ratio} = \frac{\text{Consistency Index}}{\text{Random Index}}, \quad (26)$$

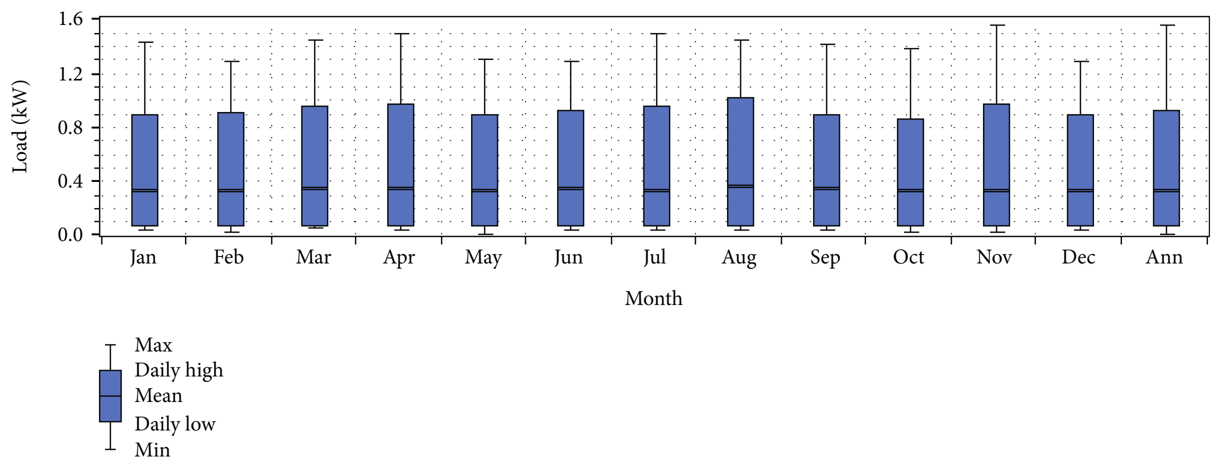


Figure 5: Annual consumption after applying random changes.

Table 3: Input required data.

| Country | Capital | Lat | Long | Electricity Price ($) [82, 83] | Annual interest rate (%) [84] | Time Zone (GMT+) | Annual average radiation [85] | Annual average clearness index |
|---|---|---|---|---|---|---|---|---|
| Bahrain | Manama | 26.3 | 50.7 | 0.048 | 3.25 | 3 | 5.605 | 0.621 |
| Cyprus | Nicosia | 35.2 | 33.4 | 0.257 | 0.5 | 3 | 5.202 | 0.627 |
| Egypt | Cairo | 30.1 | 31.4 | 0.043 | 11.25 | 2 | 5.355 | 0.613 |
| Iran | Tehran | 35.7 | 51.3 | 0.005 | 18 | 3.5 | 4.898 | 0.593 |
| Iraq | Baghdad | 33.2 | 44.2 | 0.013 | 4 | 3 | 5.024 | 0.592 |
| Jordan | Amman | 32 | 36 | 0.100 | 3.75 | 3 | 5.024 | 0.593 |
| Kuwait | Kuwait City | 29.2 | 48 | 0.029 | 2.75 | 3 | 5.575 | 0.633 |
| Lebanon | Beirut | 33.8 | 35.5 | 0.005 | 7.75 | 3 | 5.329 | 0.632 |
| Oman | Muscat | 23.6 | 58.3 | 0.026 | 3 | 4 | 5.674 | 0.616 |
| Qatar | Doha | 25.3 | 51.6 | 0.032 | 3.75 | 3 | 5.334 | 0.586 |
| Saudi Arabia | Riyadh | 24.9 | 46.7 | 0.048 | 3 | 3 | 5.778 | 0.633 |
| Syria | Damascus | 33.4 | 36.5 | 0.010 | 6.22 | 3 | 5.088 | 0.601 |
| Turkey | Ankara | 39.9 | 32.8 | 0.051 | 13 | 3 | 4.404 | 0.561 |
| UAE | Abu Dhabi | 24.4 | 54.7 | 0.081 | 3.75 | 4 | 5.616 | 0.613 |
| Yemen | Sana'a | 15.5 | 44.2 | 0.094 | 27 | 3 | 6.391 | 0.662 |

where the random index for 8 attributes is 1.4 (from Table 2).

*Step 7.* Synthesis of Model.

$$Q_{ij} = \frac{\text{Consistency Ratio}}{x_{ij}} \tag{27}$$

## 4. Input Data

The daily household consumption examined in this study is considered equal to 8.1 kWh/day or 3 MWh/year [81]. The hourly consumption diagram of this consumer is shown in Figure 4.

HOMER software generates electricity data over a yearly period using 24-hour electricity consumption data and random variability parameters day by day and hour by hour. This is obtained for each hour by multiplying the $\alpha$ parameter by the number of electricity consumed in the previous hour using the following equation [82]:

$$\alpha = 1 + \delta_d + \delta_{ts}, \tag{28}$$

where $\delta_d$ is equal to the daily deviation value, and $\delta_{ts}$ is the time step deviation value. For this purpose, the variables of random changes for daily and hourly electricity consumption are set equal to 15% and 20%, respectively. The studied annual consumption considering random changes is drawn in Figure 5.

To simulate the solar system in the HOMER software, the geographical location, the grid electricity price in each country, the annual interest rate, and the time zone of the city are needed. In addition to these data, the HOMER software also extracts data such as annual solar radiation and air clearness index from its database and adds them to the input information. The required data are presented in Table 3.

Table 4: The cost of the equipment used in the simulation.

| Components | Capital cost ($) | Replacement cost ($) | Operating & maintenance ($/year) | Lifetime | Description |
|---|---|---|---|---|---|
| PV [86] | 2000 | 2000 | 10 | 25 years | Duration factor: 80% |
| Converter [86] | 300 | 300 | 0 | 40000 hours | Inverter efficiency: 95%<br>Rectifier efficiency: 95% |

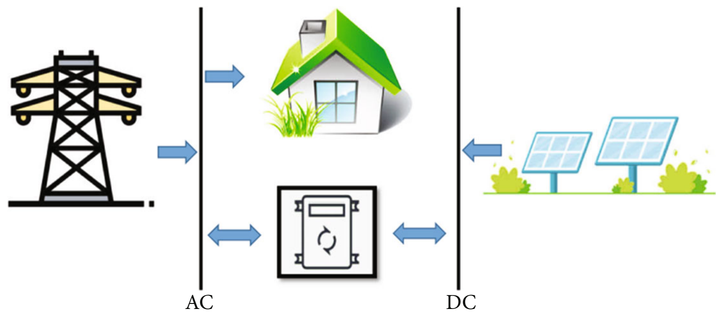


Table 5: Results of economical assessment.

| Country | City | Components | | LCOE ($/kWh) | Total NPC ($) | Payback (year) | Net purchases (kWh) |
|---|---|---|---|---|---|---|---|
| | | PV | Converter | | | | |
| Bahrain | Manama | 1 | 1 | 0.072 | 3578 | N/A | 1293 |
| Cyprus | Nicosia | 10 | 9 | -0.759 | -52429 | 5.69 | -12967 |
| Egypt | Cairo | 1 | 1 | 0.118 | 2879 | N/A | 1340 |
| Iran | Tehran | 1 | 1 | 0.149 | 2401 | N/A | 1410 |
| Iraq | Baghdad | 1 | 1 | 0.061 | 2794 | N/A | 1405 |
| Jordan | Amman | 10 | 8 | 0.094 | 4462 | 15.6 | -12451 |
| Kuwait | Kuwait City | 1 | 1 | 0.061 | 3200 | N/A | 1272 |
| Lebanon | Beirut | 1 | 1 | 0.078 | 2514 | N/A | 1326 |
| Oman | Muscat | 1 | 1 | 0.061 | 3107 | N/A | 1269 |
| Qatar | Doha | 1 | 1 | 0.068 | 3229 | N/A | 1392 |
| Saudi Arabia | Riyadh | 1 | 1 | 0.07 | 3580 | N/A | 1253 |
| Syria | Damascus | 1 | 1 | 0.072 | 2643 | N/A | 1420 |
| Turkey | Ankara | 1 | 1 | 0.138 | 2969 | N/A | 1552 |
| UAE | Abu Dhabi | 1 | 1 | 0.089 | 4184 | N/A | 1285 |
| Yemen | Sana'a | 1 | 1 | 0.25 | 2723 | 14.1 | 1107 |

The price of the used equipment, the cost of their replacement after the end of their life, and the cost of their operation and maintenance are given as input to the software, and the mentioned amounts are listed in Table 4 along with the information of the equipment used.

## 5. Results

In the present work, due to the small scale of the power supply, the number of PVs and converters in the software is considered to be 0 to 10. If the operating system is profitable, with the increase of PV and converters, the electricity production and profitability of the system will increase. In most countries, the use of one PV and one converter is economically viable, but due to high profitability in Cyprus and Jordan, 10 and 10 PV and 9 and 8 converters have been used, respectively. The simulation results are given in Tables 5–7.

*5.1. Economical Assessment.* From an economic point of view, the parameters of LCOE, total NPC, and investment return time are important. According to Table 5, in the best scenario of the present work, the lowest amount of LCOE is specific to Cyprus, which is equal to $-0.759/kWh, and the negative value of this number means that this system is profitable compared to the grid-only system, and the highest amount of LCOE is related to Yemen with an amount of $0.25/kWh. The average LCOE at the investigated stations is also calculated as $0.041/kWh.

The average of the total NPC in the surveyed stations in the Middle East is calculated to be -$544.4. The highest and lowest amounts of this parameter are related to the city of

Table 6: Results of energy assessment.

| Country | City | Renewable fraction (%) | PV production (kWh/year) | PV capacity factor (%) | Converter capacity factor (%) | Inverter losses (kWh/year) |
|---|---|---|---|---|---|---|
| Bahrain | Manama | 49 | 1739 | 19.9 | 18.9 | 87 |
| Cyprus | Nicosia | 92 | 16754 | 19.1 | 20.2 | 837 |
| Egypt | Cairo | 48 | 1690 | 19.3 | 18.3 | 84 |
| Iran | Tehran | 46 | 1617 | 18.5 | 17.5 | 81 |
| Iraq | Baghdad | 46 | 1622 | 18.5 | 17.6 | 81 |
| Jordan | Amman | 92 | 16271 | 18.6 | 22 | 810 |
| Kuwait | Kuwait City | 49 | 1762 | 20.1 | 19.1 | 88 |
| Lebanon | Beirut | 48 | 1707 | 19.5 | 18.5 | 85 |
| Oman | Muscat | 49 | 1765 | 21.1 | 19.1 | 88 |
| Qatar | Doha | 47 | 1636 | 18.7 | 17.7 | 82 |
| Saudi Arabia | Riyadh | 50 | 1781 | 20.3 | 19.3 | 89 |
| Syria | Damascus | 46 | 1606 | 18.3 | 17.4 | 80 |
| Turkey | Ankara | 43 | 1467 | 16.7 | 15.9 | 73 |
| UAE | Abu Dhabi | 49 | 1748 | 20 | 19 | 87 |
| Yemen | Sana'a | 53 | 1935 | 22.1 | 21 | 97 |

Table 7: Results of environmental assessment.

| Country | City | $CO_2$ emission by best Scenario (kg/year) | $CO_2$ emission by grid-only (kg/year) | Prevented $CO_2$ emission difference (kg/year) |
|---|---|---|---|---|
| Bahrain | Manama | 817 | 1862 | 1045 |
| Cyprus | Nicosia | -8195 | 1862 | 8195 |
| Egypt | Cairo | 847 | 1862 | 1015 |
| Iran | Tehran | 891 | 1862 | 971 |
| Iraq | Baghdad | 888 | 1862 | 974 |
| Jordan | Amman | -7869 | 1862 | 7869 |
| Kuwait | Kuwait City | 804 | 1862 | 1058 |
| Lebanon | Beirut | 838 | 1862 | 1024 |
| Oman | Muscat | 802 | 1862 | 1060 |
| Qatar | Doha | 880 | 1862 | 982 |
| Saudi Arabia | Riyadh | 792 | 1862 | 1070 |
| Syria | Damascus | 897 | 1862 | 965 |
| Turkey | Ankara | 981 | 1862 | 881 |
| UAE | Abu Dhabi | 812 | 1862 | 1050 |
| Yemen | Sana'a | 700 | 1862 | 1162 |

Amman in Jordan ($4462) and the city of Nicosia in Cyprus ($-52429), respectively.

The implementation of the solar scenario in the countries of Cyprus, Yemen, and Jordan has a return on investment time of 5.69 years, 14.1 years, and 15.6 years, respectively, and these values are calculated in comparison with the grid-only system. Other investigated stations have no return on investment time.

*5.2. Energy Assessment.* According to the data extracted from the HOMER software (Table 6), the average exchange of electricity with the grid in all the investigated cities is equal to -539.6 kWh. The exchange of electricity with the grid in this scenario in the two cities of Nicosia (Cyprus) and Amman (Jordan) were negative numbers, which were -12967 kWh and -12451 kWh, respectively. This means that, purely, the electricity produced by the solar cells has been sold to the grid.

The fraction of renewable energy, which indicates the amount of electricity produced by solar cells, is the highest in Cyprus and Jordan and is equal to 92%; in other countries, this amount is between 43% and 53%. The average fraction of renewable energy in the investigated stations is calculated at 53.8%.

The highest amount of electricity produced by solar panels is calculated in Cyprus (16754 kWh/year) and the lowest amount in Turkey (1606 kWh/year). The average of this parameter in the investigated stations is equal to 3673.3 kWh/year.

Also, the PV capacity factor in Sana'a (Yemen) and Ankara (Turkey) was calculated as 22.1% and 16.7%, respectively, which are the highest and lowest values among the investigated countries. The average of this parameter in all the investigated stations in the Middle East is equal to 19.38%.

The capacity factor of the electric converter in the countries of Jordan and Yemen has the highest value at 22% and 21%, respectively. In the countries of Turkey and Syria, this parameter is equal to 15.9% and 17.4%, respectively, and has its lowest value. The average of this factor in all investigated regions is equal to 18.76%.

The losses caused by the conversion of DC to AC in the inverter are directly related to the amount of electricity produced in the system. Therefore, as in this scenario, Cyprus and Turkey account for the highest and lowest amounts of electricity production, and they have the highest and lowest amounts of losses. These values are equal to 837 kWh/year in Cyprus and 37 kWh/year in Turkey.

*5.3. Environmental Assessment.* The annual consumption of the residential house under investigation is 2945 kW, which produces 1862 kg of $CO_2$ annually if the grid electricity is fully used. In the best scenario of the present work, the two cities of Nicosia (-12967 kg/year) and Amman (-12451 kg/year) have negative $CO_2$ production due to the sale of electricity to the grid. In these two cities, the investigated solar system not only does not produce $CO_2$ but also prevents it. In other investigated cities, due to the supply of a part of the consumed electricity by the national electricity grid, some $CO_2$ is produced, which is naturally less than the electricity produced by the grid-only system.

The difference in $CO_2$ produced by the grid-only system with the best scenario for the consumer in each region is listed in Table 7. This scenario prevents the emission of 29321 kg of $CO_2$ at all the investigated stations due to the use of solar energy.

*5.4. Ranking Analysis.* To perform analyses using MCDM methods, it was necessary to weigh the influential parameters. Table 8 shows the investigated parameters, whose weights were obtained by asking 10 renewable energy researchers. Based on the results of Table 8, the highest weight is related to the LCOE parameter and the lowest weight is related to the renewable fraction parameter. In Table 9, the numerical values of the unstimulated studied parameters for the studied stations are presented. Figure 6 shows the ranking results of different methods. The LCOE, net purchases, renewable fraction, PV capacity factor, and $CO_2$ emission parameters are the output of the HOMER software, and the land price, natural disaster risk, and population parameters are taken from the relevant references [87–89]. The average of different rankings is given as the final ranking in Figure 6. From the results, it can be seen that the top stations are Cyprus, Jordan, and Egypt, and Kuwait, Oman, and Syria stations are the most unsuitable stations.

Table 8: Weight of under study parameters.

| Parameter | Final scores |
|---|---|
| LCOE | 0.42488 |
| Net purchases | 0.31801 |
| Renewable fraction | 0.28649 |
| PV Capacity factor | 0.32214 |
| Population | 0.29445 |
| Natural disaster risk | 0.29193 |
| Land price | 0.38046 |
| $CO_2$ emission | 0.39880 |

Table 9: The value of under study parameters (unstimulated).

| Country | Population (-) [87] | Natural disaster risk (%) [88] | Land price (k$/m$^2$) [89] |
|---|---|---|---|
| Bahrain | 157,474 | 0.95 | 1.54470 |
| Cyprus | 116,392 | 2.78 | 2.22750 |
| Egypt | 9,539,673 | 20.65 | 0.48413 |
| Iran | 8,846,782 | 18.48 | 2.09210 |
| Iraq | 8,126,755 | 8.65 | 2.11201 |
| Jordan | 4,302,730 | 3.48 | 1.30221 |
| Kuwait | 2,989,000 | 2.56 | 7.76348 |
| Lebanon | 361,366 | 3.52 | 3.81250 |
| Oman | 31,409 | 7.27 | 1.89706 |
| Qatar | 587,055 | 1.17 | 4.41156 |
| Saudi Arabia | 7,676,654 | 9.64 | 1.72002 |
| Syria | 2,354,000 | 12.16 | 2.00000 |
| Turkey | 5,663,322 | 16.23 | 0.85638 |
| UAE | 1,482,816 | 6.52 | 3.73550 |
| Yemen | 2,545,000 | 24.26 | 2.58323 |

In the following, economical-technical-energy analyses for the top solar station in the Middle East (Cyprus) were done. As can be seen in Figure 7, after the fifth year, the solar-grid system is economically superior to the grid-only system. Because the sale of excess electricity to the grid generates income for the solar-grid system, but the annual maintenance costs create a negative cost for the grid-only system. According to Figure 7, after the end of the useful life of the project (25 years), the solar-grid hybrid system will have an economic benefit of $76,360 compared to the grid-only system.

Figure 8 shows the amount of electricity produced in different months by the PV-grid hybrid system. From the results, it can be seen that 92% of the produced electricity (16754 kWh/y) is supplied by solar cells and the rest by the national grid. Also, considering the need for more electricity for cooling in the hot months of the year, it can be seen from

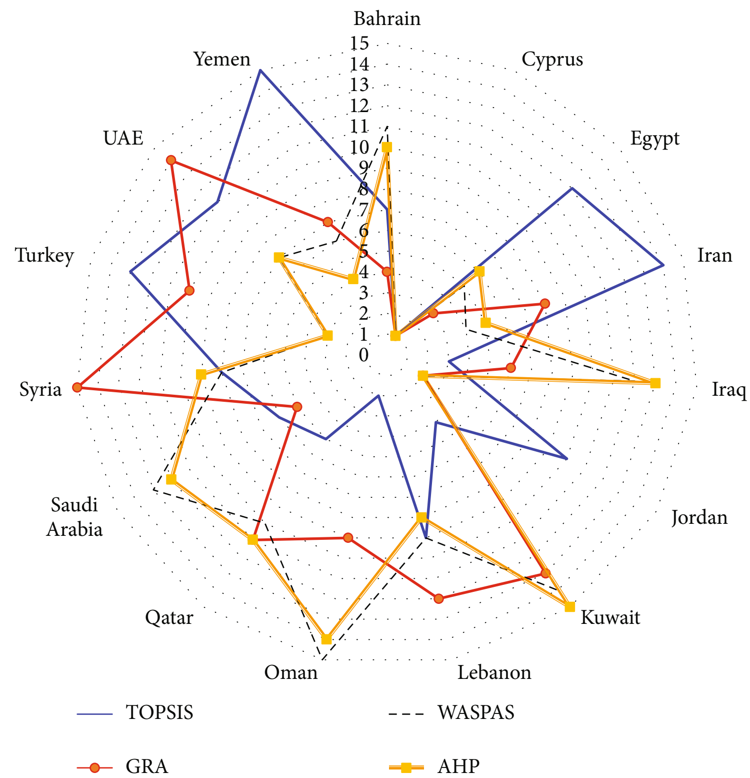


Figure 6: Results of ranking analysis.

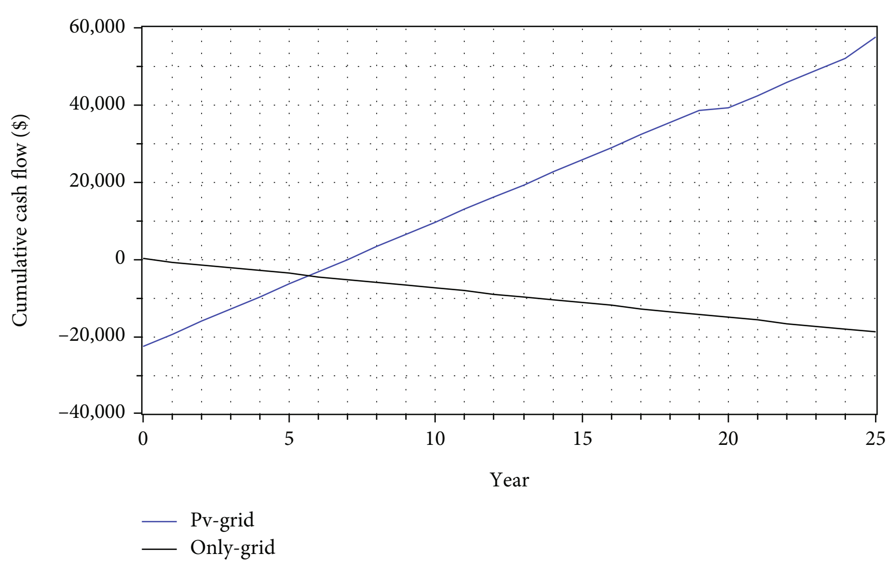


Figure 7: Economic comparison of PV-grid system with an only-grid system in 25 years lifetime of the project.

the results that solar electricity also has its highest amount in these months, which can meet the need for electricity. Also, in the cold months of the year, due to the low amount of radiation, the use of the national electricity grid is more for supplying electricity.

Figures 9(a) and 9(b), respectively, show the output diagram of solar cells and DC to AC converter for a PV-grid hybrid system. From the results, it can be seen that the maximum electricity production is 12 kW and occurs around 12 : 00 to 14 : 00, which is also the time when the electric converter has the highest performance and works with a maximum capacity of 9 kW. During the hours when there is no sunlight, solar cells do not produce electricity, so the electrical converter does not work and electricity is supplied through the grid.

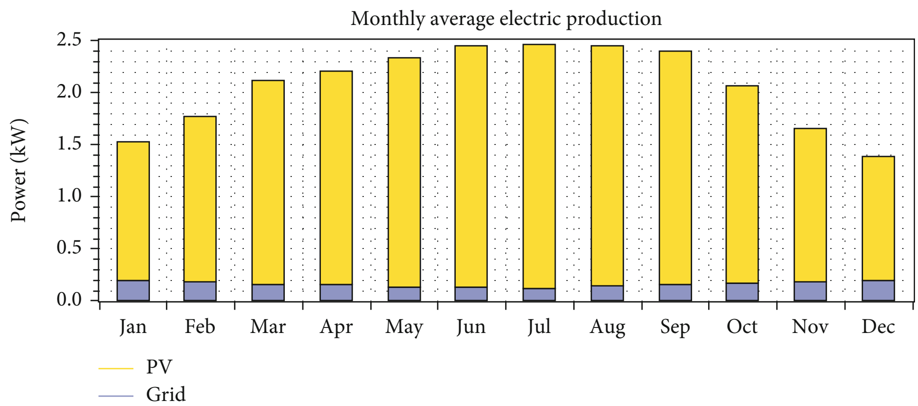


FIGURE 8: Monthly average electricity production.

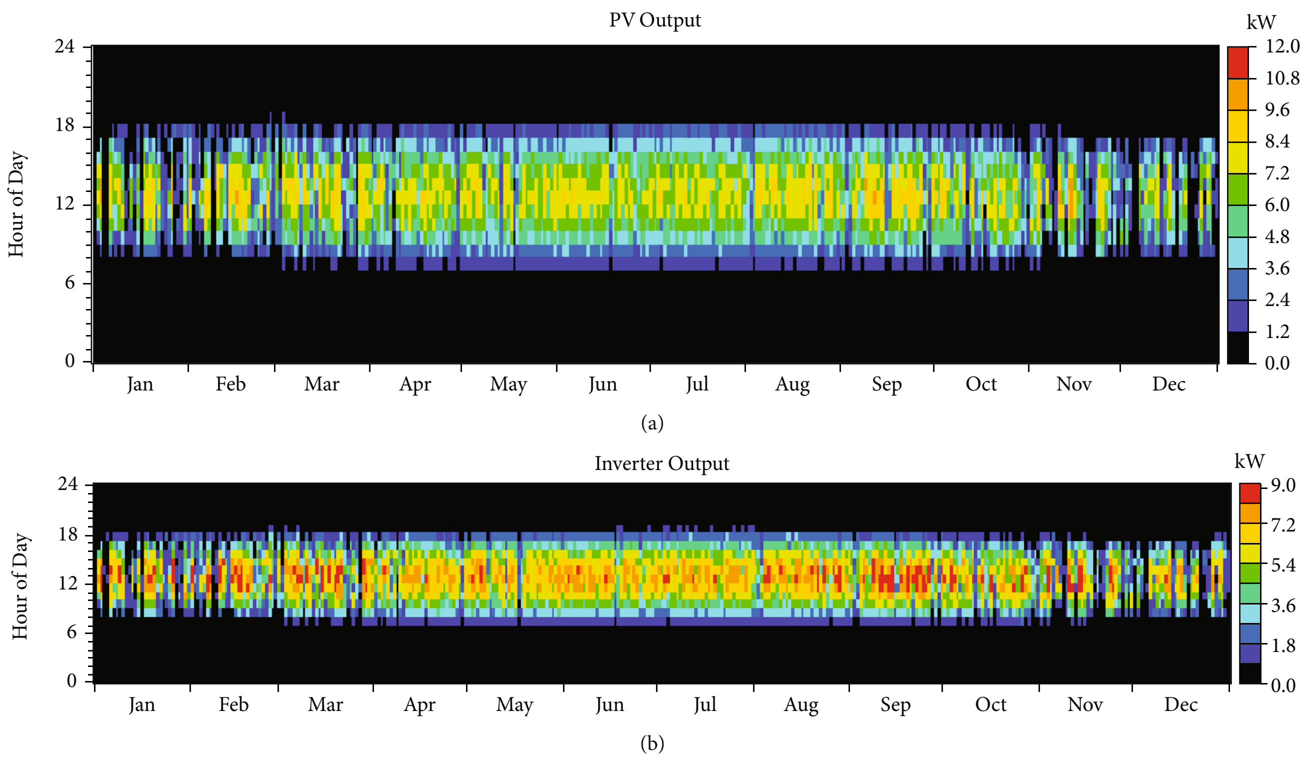


FIGURE 9: Performance contours of (a) PV output and (b) inverter output.

## 6. Conclusion

The abundance and low cost of fossil fuels in the Middle East region have made a comprehensive study on the potential of using a home-scale solar system in this region not yet been carried out. The present work is the first study in the field of supplying the required electricity of a residential house connected to the grid by solar cells in the Middle East. For evaluations, the capitals of the countries have been selected. The simulations were performed for a period of 25 years by HOMER V2.81 software. Technical, energy, economic, and environmental analyses were conducted for all 15 capital cities. MCDM methods included TOPSIS, GRA, WSM, and AHP for station ranking. Experts' opinions were also used to weigh the effective parameters. The investigated parameters were a combination of HOMER software outputs and other economic, social, and environmental risk parameters. The main results of the present work are

(i) The lowest and highest values of LCOE with values of \$-0.759 and \$0.25 are related to Nicosia and Sana'a, respectively

(ii) The solar system only at three stations: Nicosia, Amman, and Sana'a, has a payback time compared to the grid-only system

(iii) Only in Nicosia and Amman stations is the net electricity purchased from the grid negative

(iv) The solar fraction at the investigated stations is between 43% and 92%. The highest solar fraction is related to Nicosia and Amman, and the lowest solar fraction is related to Ankara

(v) The highest and lowest annual solar electricity production are in Nicosia (16754 kWh) and Ankara (1467 kWh), respectively

(vi) The capacity factor of solar cells for the studied stations is 16.7-22.1%.

(vii) The total prevention of pollutant emission in 15 investigated stations is more than 29 tons/year

(viii) The weighting results showed that the LCOE and renewable fraction parameters have the highest and lowest weights, respectively

(ix) The results of the AHP and WSM methods are close to each other, but the results of the GRA and TOPSIS methods are very different from other methods and from each other

(x) Cyprus station is the best station, and Kuwait station is the worst station

## Nomenclature

i: Annual interest rate (%)
MCDM: Multicriteria decision making (-)
FTOPSIS: Fuzzy technique for order performance by similarity to ideal solution (-)
CRF: Capacity recovery factor (-)
MENA: Middle East and North Africa (-)
Lat.: Latitude (-)
Long.: Longitude (-)
N: Useful lifetime (year)
PV: Photovoltaic
NPC: Net present cost ($)
LCOE: Levelized cost of electricity ($/kWh)
GMT: Greenwich Mean Time (-)
$\alpha$: Constant parameter (-)
TOPSIS: Technique for order of preference by similarity to ideal solution (-)
$X_{ij}$: Matrix containing input data (-)
$\bar{X}_{ij}$: Normalized matrix (-)
$V_{ij}$: Weighted normalized matrix (-)
$W_j$: Weight of $j$th criterion (-)
V+: Maximum value of $V_{ij}$ (-)
V-: Minimum value of $V_{ij}$ (-)
$S_i^+$: Euclidean distance for ideal best (-)
$S_i^-$: Euclidean distance for ideal worst (-)
$P_i$: Performance score (-)
GRA: Grey relational analysis (-)
$\delta_d$: Daily deviation value
$\delta_{ts}$: Time-step deviation value
$T_c$: Temperature of the PV cell in the current time (°C)
$T_{c,\ STC}$: PV cell temperature in standard test conditions (25°C)
$C_{NPC,\ total}$: Total net present cost ($)
$\overline{G_{T,STC}}$: Incident radiation on the cell's surface under standard conditions ($1\,kW/m^2$)
$\overline{G_T}$: Incident radiation on the cell's surface on a monthly basis ($kW/m^2$)
$Y_{PV}$: Output power of solar cell under standard conditions (kW)
$f_{PV}$: Derating factor (%)
$P_{PV}$: Output power of PV cells (kW)
$R_{proj}$: Lifetime of project (year)
$C_{ann,\ total}$: Total annual cost ($)
$E_{load\ served}$: Real electrical load by system (kWh/year)
$\alpha_p$: Power temperature coefficient (%/°C)
$\Delta_{0i}(k)$: The grey relational coefficient between $X_{ij}$ and $X_{0j}$ (-)
$x_i^*(k)$: Normalised data (-)
$x_i^0(k)$: Input data for specific criteria (-)
$\zeta$: Distinguishing coefficient ($\zeta = 0.5$)
$\gamma_i$: Grey relational grade (-)
$\omega_k$: Weight of kth criterion (-)
$n$: Quantity of criteria (-)
WSM: Weighted sum method (-)
$Q_i^{(1)}$: Total relative importance (-)
AHP: Analytic hierarchy process (-)
$S_{ij}$: Saaty's matrix (-).

## Data Availability

All data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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