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# Design of an isolated renewable hybrid energy system: a case study

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**Abstract**

In addition to the fact that most renewable energies such as solar and wind energy have become more competitive in the global energy market, thanks to the great development in conversion technologies, it believes that renewable energy can play a crucial role in global environmental issues. However, in Palestine, the situation is different from anywhere else; renewable energy is not only an economic option, but an absolute necessity to get out of the energy crisis that Palestinian cities suffer from long years ago and continue nowadays**.** The cornerstone of the present research is focusing on the availability of renewable energy resources in Jenin Governorate (JG)—West Bank (WB)—Palestine. Two-year time-series of hourly solar, wind, biomass, and 1-year hourly electrical load data are used in the analysis in this paper. The energy potentials were estimated using System Advisor Model software (SAM), and the optimum combination and sizing of the hybrid renewable energy system were determined using Hybrid Optimization of Multiple Energy Resources (HOMER). The proposed Hybrid Renewable Energy System (HRES) consists of an 80 MW PV solar field, 66 MW wind farm, and 50 MW biomass system with an initial investment of $323 M. The proposed HRES generates 389 GWh/yr and is enough to meet 100% of the electrical demand of JG (372 GWh/yr) with excess in electricity generation of about 4.57% and the unmeet electric load is about 109.6 MWh/yr which is equivalent to less than 2 h off in a year. The estimated Levelized Cost of Energy (LCOE) was found as 0.313 $/kWh.

**Keywords** Palestine · West Bank · Jenin · Renewable energy · Energy mix · Hybrid energy system

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## Introduction

Energy is the driver of our daily life. It is responsible for economic growth, prosperity, and globalization. However, since the last century, the primary sources of energy are fossil fuels. Due to a complex combination of factors, including the prospects of resource constraint, population growth, security of supply, and heightened environmental concern, the world is pronounced under an energy crisis [1]. The energy crisis has accelerated by the Russian invasion of Ukraine on 24 February 2022. The whole world has been affected by this war which spread its dark shade on the world. Accordingly, the world needs to make energy investments that look beyond the immediate term and are viable for the future [2].

The world is moving towards achieving a rapid transition from conventional electricity generation based on burning fossil fuels, which is considered the main culprit in the dangerous environmental phenomena that threaten human life on the earth, towards clean and environmentally friendly energies [3, 4]. Many studies that dealt with the problem of energy in the Palestinian territories have confirmed that the renewable energy source (REs), mainly solar, can play an important role in solving energy problems in the West Bank (WB) and Gaza Strip (GS) [5, 6]. Even though many researchers classified wind energy in the GS and the WB as having a low energy potential, it constituted a large percentage of the research of those interested in renewable energies, [7–12]. Biomass energy also exists in the research field. The literature [13–17] highlighted the key future of the potential of bioenergy in Palestine territories.

This research differs from its predecessors in that it studies the capability of each Governorate to generate its energy requirement separately from the rest of the other municipalities to achieve decentralization and energy independence. In this context, Alsamamra and Shoqeir evaluated the wind power potential in Eastern-Jerusalem [9]. Nassar and Alsadi analyzed the solar radiation for all municipalities of GS and WB [18], and modelled the solar irradiation and determined the optimum tilt and azimuth angles for Jenin Governorate [19–21]. Al-Maghalseh and Saleh designed and analyzed the cost of biogas-based power plants for Jenin [14], and Kitaneh et al. analyzed the wind energy in some areas of Palestine [22]. Alsadi and Nassar evaluated the impact of shadow and other design parameters on the productivity of the Jericho PV solar field [23, 24].

Others handled the REs from various points of respect, motives, and challenges [25, 26], strategies and policies [27–29], achievements and barriers [30], creating HRESs [31], locating and mapping [5, 32], experiences [33, 34], evaluating and modelling [35–37], estimating and assessing [6, 38–41], utilization [42], and experiences and lessons learning from neighbouring countries [43–46].

This research aims to design and simulate an electrical power generation system based on HRESs consisting of solar energy, wind energy, and biomass energy to cover 100% of the electrical load of the Jenin Governorate. The simulation processes have been established by the SAM. SAM is a free techno-economic tool that facilitates decision-making for people in the renewable energy industry. While the design and sizing of the HRES have been carried out by HOMER-pro software. This software application is used to design and evaluate technically and financially the options for off-grid and on-grid power systems for remote, stand-alone, and distributed generation applications. It allows considering a large number of technology options to account for energy resource availability and other variables.

The key future of this paper is highlighting the individual REs potentials (electrical and thermal solar, wind, and biomass energy) in Jenin Governorate, making this study the most comprehensive in this field. In this context, the present study has the following contributions:

1. Highlighting the economic feasibility of local renewable energies.
2. Locating and mapping renewable energy projects for balanced sustainable development requirements.
3. Recommendations for 100% demand cover using (HRES).

## Key figures about Jenin Governorate

Jenin city is located on the northernmost of the WB (Fig. 1) at coordinates 32° 27′ 40″ N, 35° 18′ 00″ E and has an area of about 37,342 dunams (37.3 km$^2$). The population in Jenin is counted as 314,866 according to the Palestinian Central Bureau of Statistics in Ramallah for the year census 2021 [47].

Based on the information provided by the North Electrical Distribution Company-Palestine for the year 2020, the hourly electrical load of JG is depicted graphically in Fig. 2. The annual electrical energy consumption was 371.935 GWh/yr, with a daily average of 1019 MWh/day. As shown in Fig. 2, the hourly load is fluctuated between 30 MW from 2:00 to 4:00 and around 60 MW extended from 11:00 to 13:00 with an average of 43 MW. The peak load was 89.1 MW and this occurred on June 20th at 13:00. While the minimum value was 12.2 MW and this occurred on May 18th at 8:00. The load factor is around 0.48. A value of 42.5 MWh was recorded as an annual average of electricity consumption in JG.

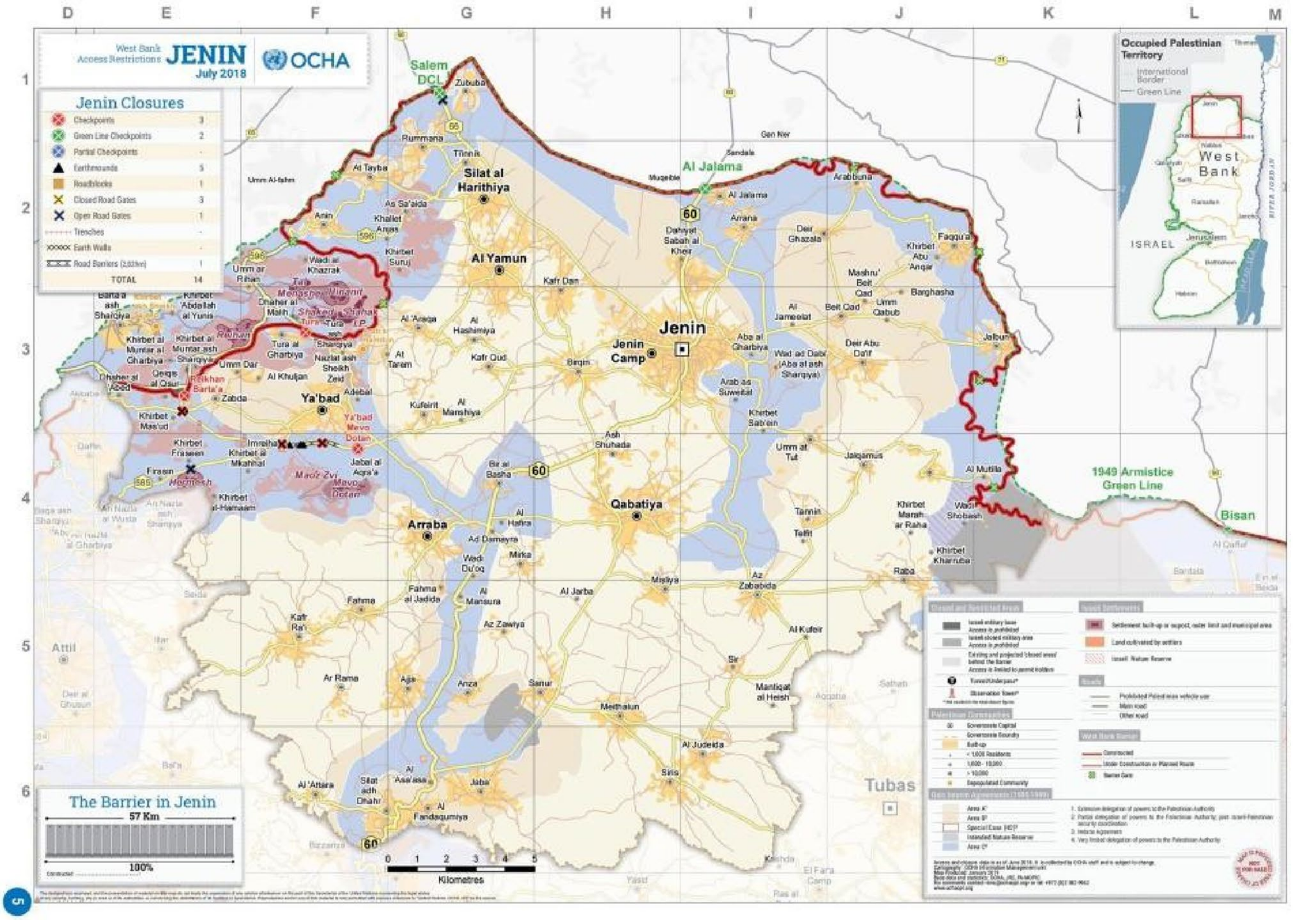



**Fig. 1** Map of Jenin Governorate (source: https://en.wikipedia.org/wiki/Jenin_Governorate)

Construction of the electric power plant in JG was started in 2016, and is expected to be completed in 2025, with a total capacity of 450 MW, and for $620,000,000. The Jenin power plant is expected to meet about 50% of the total electricity consumption in Palestine [48].

Although all previous studies unanimously agreed on the availability of solar energy in all parts of the Palestinian territories, including the JG, the unstable political situation in the region is considered a deterrent to investment in the Palestinian energy market. Despite all this, some small projects have been completed in the field of solar energy, and there are plans to establish more of them as the only way out of the energy crisis in the Governorate. Table 1 presents an inventory of solar projects in Jenin Governorate up to the year 2020 [29].

## Methodology

The approach followed in this research is demonstrated in the flowchart depicted in Fig. 3. The approach begins with importing data that include: meteorological, energetic, and economic data. The energetic and economic key figures of the solar and wind energy potential have been determined via SAM software [49]. Then, the data have been processed by the HOMER software, to optimize the design and size of HRES. The main constraints that hold during the simulation process are

1. The proposed system consists only of renewable resources.
2. The proposed system must meet 100% of the electricity load.
3. Utilization of all available biomass.

### Constraints and uncertainties

The proposed isolated (HRES) should be providing a sustained supply of energy independently. As it is the unique source for fulfilling the load requirement of the Governorate, therefore, the power supply reliability operational constraint (PSROC) was expressed as [44]

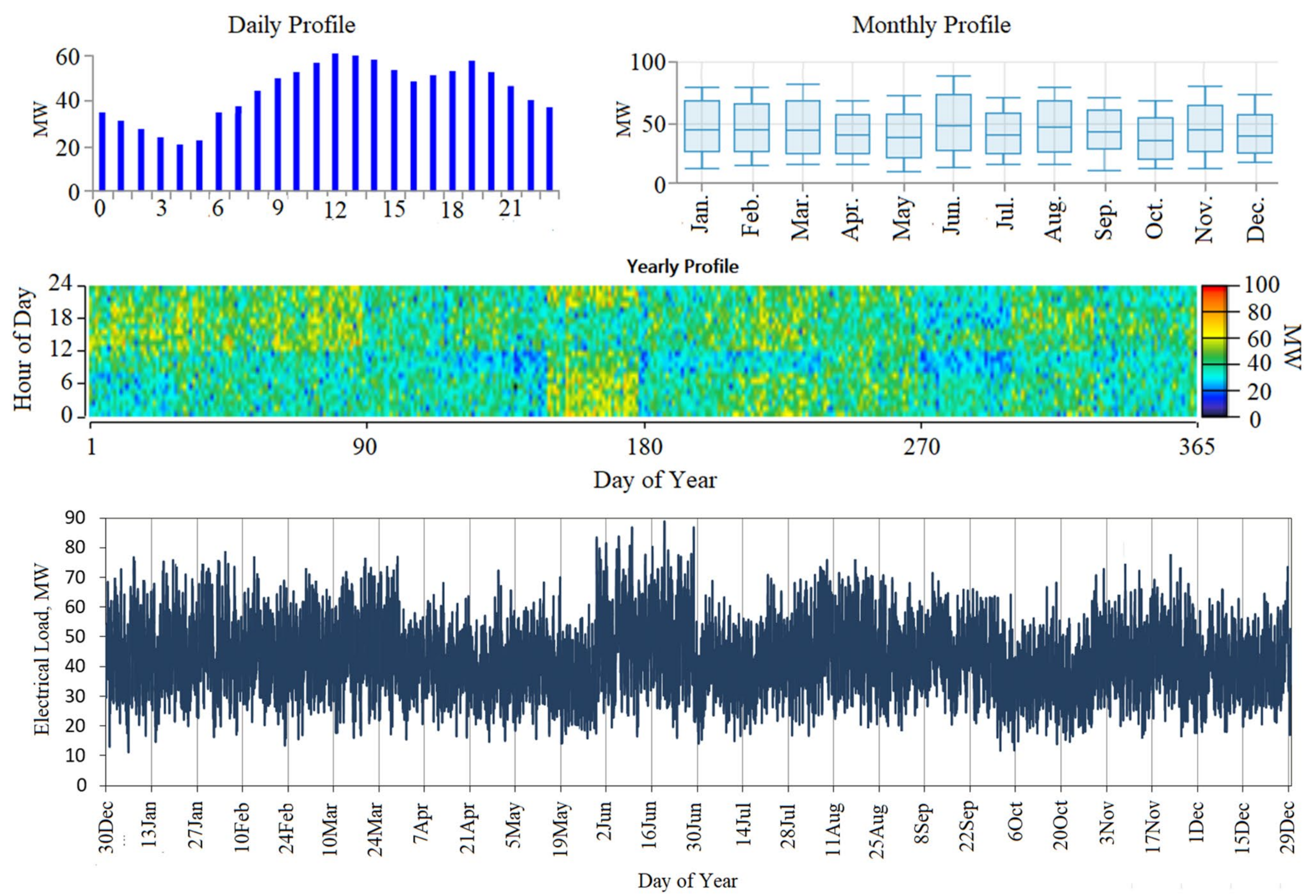



**Fig. 2** Load characteristics for Jenin Governorate

**Table 1** Details on PV solar system investments in Jenin

| State | Project | Capacity (MW) |
|---|---|---|
| Operational | Ajja solar project | 2 |
| | Maithalon | 3 |
| | Ya'bad Governorate | 4 |
| Under development | Noor Jenin, PIF | 3 |

$$\text{PSROC} = \frac{\sum_{t=1}^{8760} E_{\text{Load}}(t) - (E_{\text{PV}}(t) + E_{\text{wind}}(t) + E_{\text{biomass}}(t))}{\sum_{t=1}^{8760} E_{\text{Load}}(t)} \leq 0.02\%, \tag{1}$$

where $E_{\text{Load}}(t)$ refers to the electrical load in GWh, $E_{\text{PV}}(t)$, $E_{\text{wind}}(t)$, and $E_{\text{biomass}}(t)$ are the energy generated by the PV solar field, wind farm, and bioenergy (HRES) in GWh, and $t$ indicates to the time. The value of PSROC implies a compromise between the high reliability and the security of the power supply of the proposed (HRES). PSROC of 0.02% means that the load disruption is not more than 2 h over a whole year. Therefore, PSROC is considered in the proposed sizing procedure as a constraint to the (HRES). PSROC has a value between [0–1.0]. The zero value of PSROC means that the load requirement is fully fulfilled by the (HRES), while the less than unity value indicates to a sizing deficiency. However, the zero value mandates an expensively cost HRESs.

The major sources of uncertainty are related to the most important parameters in predicting the PV solar energy yield:

1. The solar radiation resources
2. Electrical–thermal PV module characteristics
3. System output and performance—including long-term effects.

The uncertainty in solar radiation resources is in part related to the instruments about 2.76% [50], in part to the translation of measured global horizontal irradiance to plane-of-array irradiance (POA) [51] about 6% [52], and the last part is the effective irradiance, which represents the irradiance converted to electrical current within the module. It differs from POA due to several mechanisms:

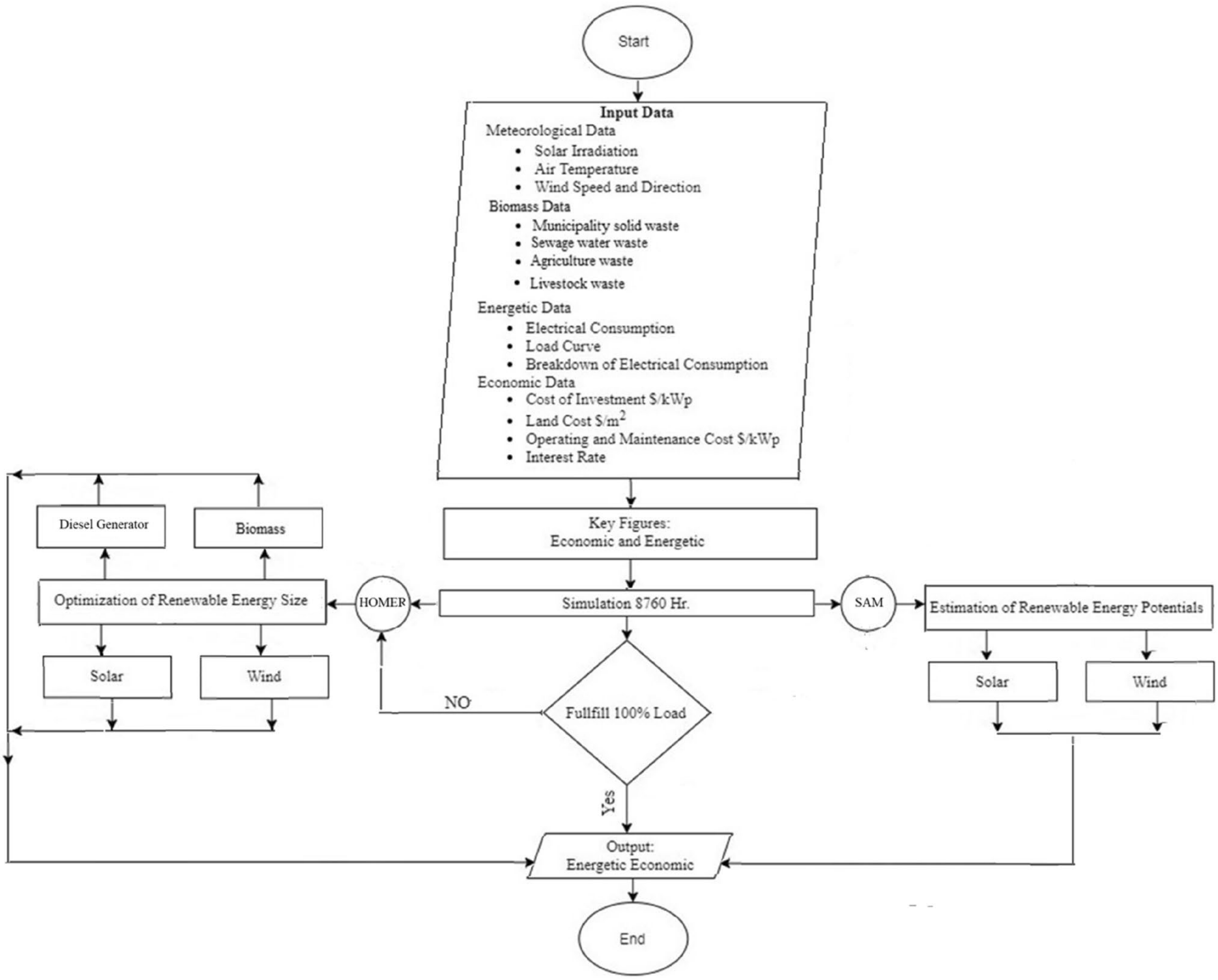



**Fig. 3** Flowchart of the dynamic simulation and optimization procedure

optical losses; and losses due to shading and soiling which is about 4% [53].

In energy rating, the dominating uncertainties raise from PV module characteristics. The module performance at real operation conditions irradiance and temperatures are different from STC. There are many correlations and heat transfer models for estimating the cell temperature and also converting the electrical characteristics at STC to real operating conditions [54]. Furthermore, the thermal–electrical characteristics differ with the type of module technology [type of technology such as monocrystal silicon (m-Si) and polycrystalline silicon (p-Si) and amorphous silicon (a-Si)] [55]. Reise et al. estimated the uncertainties due to module characteristics and module technology as 3.5 and 2.13%, respectively [56].

The system output and performance uncertainties come from the complete conversion chain of a PV system. This conversion chain which is about 2.5% includes many steps, from PV module DC output to inverter and transformer efficiencies, due to inefficient maximum power point tracking or mismatch among modules, and adds mismatch and ohmic losses and also losses due to poor system design or poor workmanship. The uncertainty related to degradation for long-term stability is estimated as 0.4% for 30 years.

In aggregate, these uncertainties contribute to uncertainty in predicted energy yield as [52]

$$\text{The total uncertainities} = \sqrt{\sum (\text{individual uncertainty})^2}. \quad (2)$$

Figure 4 presents a vertical Chevron list of individual uncertainties associated with modelling PV systems; furthermore, uncertainties of individual models are summarized in Table 7 (in the Appendix).

From an economic point of view, the major sources of uncertainty are data availability, model selection, and

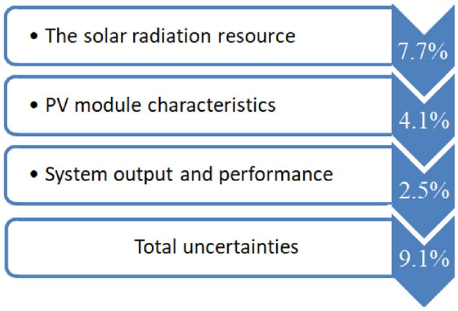



**Fig. 4** Uncertainties associated with the simulation of PV energy yield

parameter estimation. For example, variation in the availability of renewable energy would affect the output energy profile of the relevant energy-conversion technologies (e.g., solar and wind). The price of renewable energy facilities is also considered a source of uncertainty. Nassar and Alsadi [6] reported that the variance in the prices of the PV panels exceeded 360% as the prices ranged from $980/kW to $4510/kW. Also, a significant difference was observed in the values presented in the references to the quantities of animal and agricultural waste which is considered a source of uncertainty [57, 58].

## Results and discussion

### Solar energy

The obtained results by SAM are plotted to show the potential of solar energy in the Jenin Governorate. Figure 5 demonstrates the average of 2 years (2020–2021) hourly time-series global horizontal and diffuse solar irradiation, provided by the Energy Research and Studies Center at Palestine Technical University—Tulkarm—Palestine.

The SAM library contains a very large number of solar modules of various designs, technologies, manufacturers, and capacities, and it is confusing to choose one of them without a scientific basis. Nassar et al. [59] studied the performance of many of these types to figure out the best type to work under the climatic conditions of several locations in Libya. The criterion of selection was the minimum value of LCOE. In this research, a map was drawn indicating the most appropriate types of solar modules for each of the regions under consideration. By comparing the climatic conditions between the cities of Libya and the city of Jenin, it is found that the Al-Jabal Al-Akhdar region is the closest climatically to it, and accordingly, the same type of solar module was adopted for Jenin. The selected PV module is Sunpower SPR-E19-310-COM with an efficiency of 19.1% (http://www.solardesigntool.com/components/module-panel-solar/Sunpower/2644/SPR-E19-310-COM/specification-data-sheet.html). The technical, economic, and energetic key figures of the PV solar field are tabulated in Table 8. While, Fig. 6 illustrates the hourly PV solar field power generation for the 1st day of every month from a 20 MW PV solar field power capacity.

The PV operation data were generated under real climatic and load conditions during the simulation process. The following options have been chosen:

1. The global tilted solar irradiation was calculated for HDKR model according to [18];
2. Allow the program to determine the optimum fixed mode tilt angle;
3. The heat transfer method option has been chosen to calculate the cell's temperature;
4. All the losses were kept in default option;
5. Lifetime is taken to be 30 years.

Table 2 presents data from the month-long simulation in terms of minimum, maximum, and average values and the total monthly energy generation by the PV solar field. The total annual energy generation by the PV solar field is estimated as 34,062.8 MWh. Also, it is calculated that about 80% of the domestic water heating load can be met by implementing flat plate solar heating collectors or vacuum tube solar heating collectors [60].

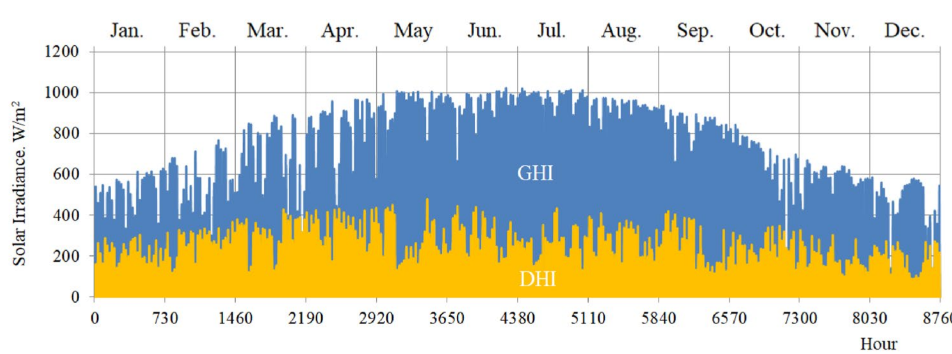



**Fig. 5** Hourly global horizontal (GHI) and diffuse solar irradiation (DHI)

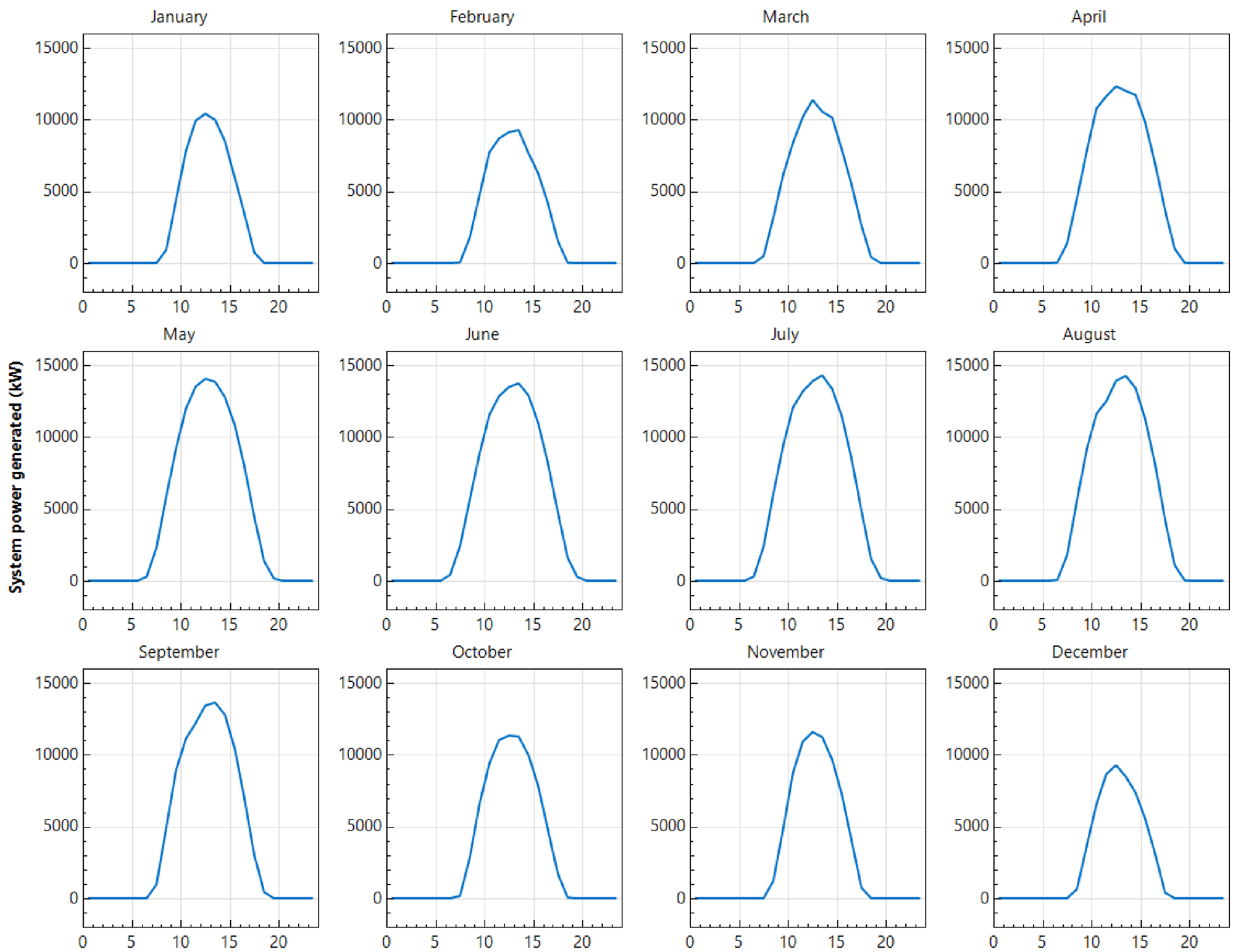



**Fig. 6** Hourly PV solar field power generation for the 1st day of every month

**Table 2** Energy generation by the PV solar field statistical data from SAM during the month-long simulation, MWh

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Max. hourly | 14.8 | 16.2 | 17.6 | 17.2 | 17.6 | 16.4 | 16.7 | 16.5 | 16.7 | 16.7 | 15.4 | 14.9 |
| Min. hourly | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Mean hourly | 2.7 | 2.8 | 3.4 | 4.2 | 4.9 | 4.9 | 5.1 | 4.9 | 4.5 | 3.6 | 3.3 | 2.4 |
| Avg. daily min | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Avg. daily max | 12.0 | 12.1 | 13.1 | 14.2 | 15.6 | 15.3 | 15.8 | 15.7 | 15.5 | 13.5 | 13.1 | 11.1 |
| Total monthly | 2037 | 1914 | 2517 | 2993 | 3636 | 3506 | 3784 | 3615 | 3251 | 2671 | 2353 | 1785 |

## Wind energy

The meteorological station in Jenin Governorate which is affiliated with the Energy Research and Studies Center at Palestine Technical University—Tulkarm—Palestine recorded very low average wind speeds during the past years (2008–2021). These averages were not greater than 2.00 m/s [61]. However, using the Google Wind-Atlas platform, one can navigate over the Governorate to locate the windiest site in the Governorate [62]. It reveals that the average wind speed in the Governorate is about 1.7 m/s in the city center and rises on the tops of the southern and eastern mountains to reach 6.5 m/s. While the wind speed increases at a height of 50 m to reach 3.5 m/s in the city center and about 7.1 m/s on the tops of the mountains. At a height of 100 m, the wind speed inside the city becomes about 4.5 m/s, while it exceeds the barrier of 8.3 m/s on the tops of the mountains, as illustrated in Fig. 7. The initial cost of the wind farm is

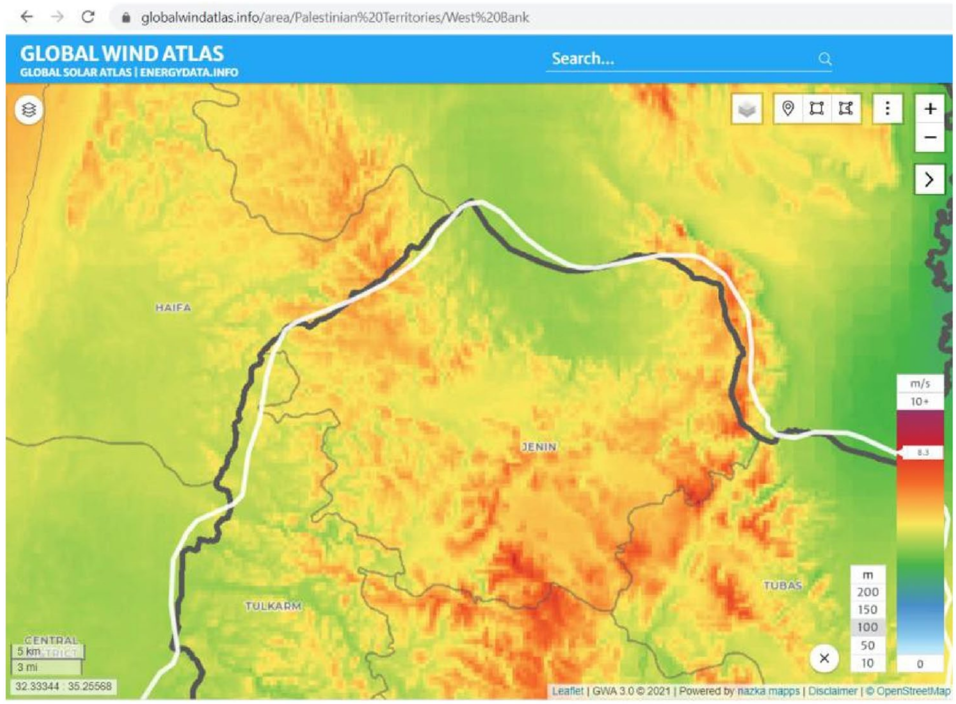



**Fig. 7** Wind speed contour map across Jenin Governorate, including Southern and Eastern mountains (source: https://globalwindatlas.info/area/Palestinian%20Territories/West%20Bank)

\$1038–2472/kW and the annual O&M costs have ranged from \$33/kW to \$56/kW [63].

Accordingly, suggested in this research to construct a wind park along the tops of southern mountains. SAM library includes about 250 types of wind turbines with different capacities ranging from 270 W to 8 MW. Many types are examined to figure out the most suitable wind turbine achieving the lowest LCOE. After comparisons, it was found that Gamesa G114 2.0 MW wind turbine is the best choice. The technical, economic, and energetic key figures of the wind farm are tabulated in Table 10. While, Fig. 8 illustrates the hourly wind farm power generation for the 1st day of every month from a 50 MW wind farm power capacity. And Table 3 presents data from the month-long simulation in terms of minimum hourly, maximum hourly, average minimum hourly, average maximum hourly values, and the total monthly energy generation by the wind farm. The total annual energy generation is estimated at 166,220 MWh.

## Biomass energy

There is no reliable information about biomass power for Palestine [64], but around the world, there are some criteria that can be used to draw a roadmap to start generating power from biomass. In China, the total capital costs ($C_{BM}$) range from low values of \$634/kW for rice husk projects to high values up to \$5304/kW for renewable municipal waste projects. In India, the range was from a low value of \$514/kW for bagasse projects to a high value of \$4356/kW for landfill gas projects. The range is higher for projects in Europe and North America, and the costs in these two geographies regions ranged from \$598/kW for landfill gas projects in North America, to a high value of \$7940/kW for wood waste projects in Europe [63]. Fixed operation and maintenance (O&M) costs ($O_{BM,}$) include: labour, insurance, scheduled maintenance, and routine replacement of plant components ranging between 2 and 6% of the total installed costs per year. The variable O&M costs $O_{BM,}$, at an average of \$0.005/kWh [63].

### Municipal solid waste (MSW)

Jenin Governorate has one landfill that is Zahrat al-Finjan sanitary landfill, which was established in 2007 with a total cell capacity of 2.25 M tons of waste. It is located in area B and managed by JSC Jenin. Originally, it was designed to take the municipal solid waste of Jenin and Tubas, for about 30–35 years. Jenin Municipality generates about 200 tons/day of solid waste [65]. The main composition of the MSW coming to the landfill in 2017 is mainly organic (55%); paper and cardboard (12%); plastic and rubber (14%), glass (1.5%), and metals (2%) [64].

### Residues in agriculture (RAW)

According to the Ministry of Agriculture's annual reports for the year 2019, the area of agricultural land in the Jenin Governorate amounted to 208,352 Dunams. This generates about 703.6 tons of organic agricultural waste. Jenin is also famous for implants and olive production. The olive

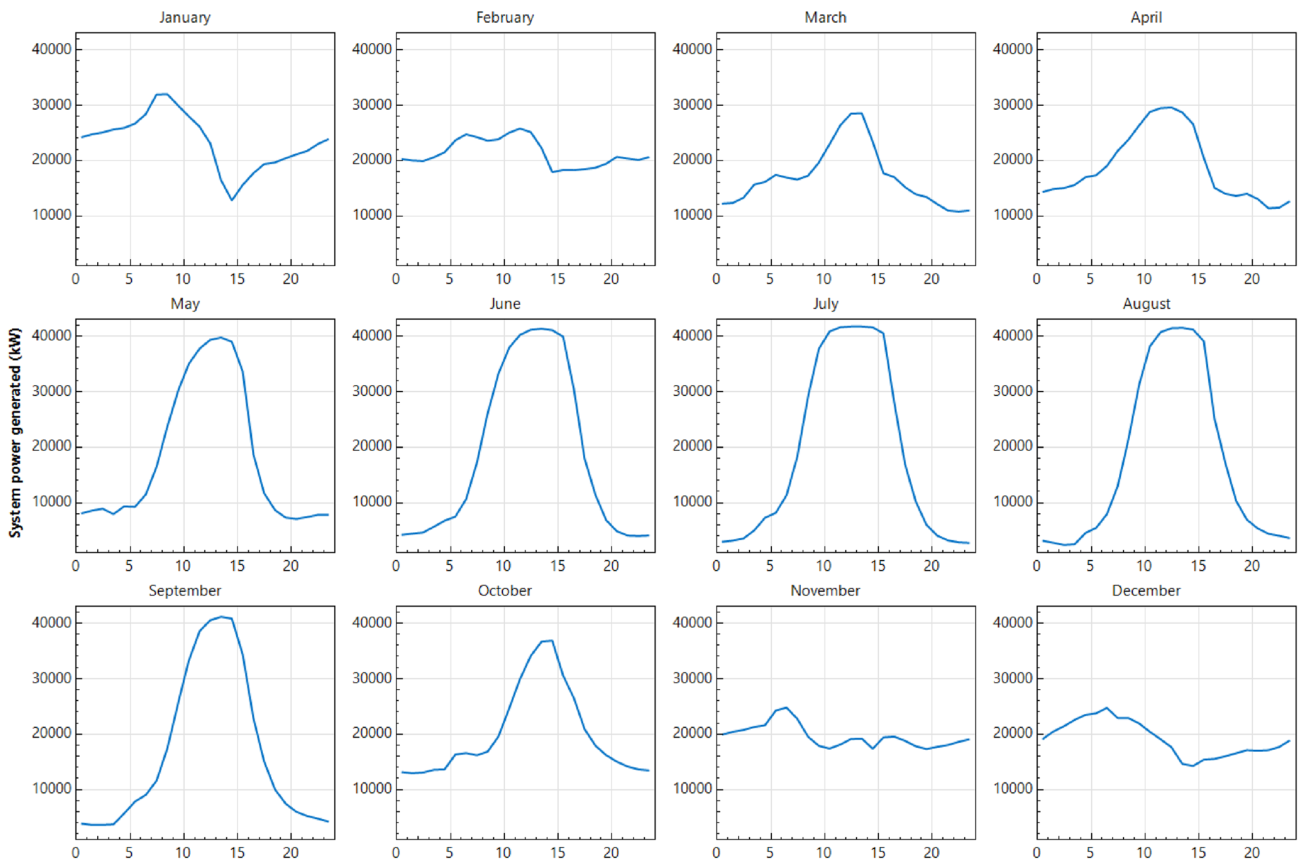



**Fig. 8** Hourly wind farm power generation for the 1st day of every month

**Table 3** Energy generation by the wind turbine statistical data from SAM during the month-long simulation

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Max. hourly | 41.7 | 41.7 | 41.7 | 41.7 | 41.7 | 41.7 | 41.7 | 41.7 | 41.7 | 41.7 | 41.7 | 41.7 |
| Min. hourly | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Mean hourly | 23.4 | 21.3 | 17.0 | 18.8 | 18.0 | 18.5 | 18.6 | 17.1 | 16.4 | 20.0 | 19.5 | 19.1 |
| Avg. daily min | 5.9 | 6.3 | 3.0 | 3.5 | 1.5 | 1.4 | 1.4 | 1.2 | 1.1 | 2.5 | 3.1 | 4.8 |
| Avg. daily max | 38.6 | 35.5 | 34.8 | 38.1 | 40.5 | 41.5 | 41.7 | 41.4 | 41.2 | 40.5 | 35.2 | 33.3 |
| Total monthly | 17,394 | 14,312 | 12,624 | 13,553 | 13,413 | 13,314 | 13,851 | 12,756 | 11,830 | 14,899 | 14,061 | 14,212 |

mill solid waste can be used as a source of a clean source of energy. The annual average amount of olive cake waste is around 45,576 tons [66]. One olive tree also produces about 25 kg of olive leaves per year and this will produce an additional amount of RAW of 73,333 tons [67]. The average calorific value of olive cake (OC) sample from the city of Jenin is 31,200 kJ/kg, in contrast to wood at 17,000 kJ/kg and soft coat at 23,000 kJ/kg, which indicates the importance of OC's potential to be used as an energy source [67].

The other waste is coming from livestock waste (LSW). Table 4 enumerates several domestic animals and birds in Jenin and presents their manure production and volume of $CH_4$ according to the statistics of PCBS for the end of 2010.

### Governorate wastewater (MWW)

According to Jenin wastewater treatment plant (WWTP) statistical data for the year 2019, the daily treated MWW is about 2305 $m^3$ [68]. The sludge to MWW ratio is about 1.02 $kg/m^3$ [69]. According to the data, the estimated energy in different forms is calculated and tabulated in Table 5. The biomass potential in Jenin Governorate is more than 205 kton/year (i.e., MSW, SWW, LSW, and

**Table 4** Number of demotic animals in Jenin [67]

| Livestock type | No. of animals | Manure production (kg/hoof/year) [57] | Manure availability coefficient (%) [58] | The volume of CH4 ($m^3$/kg manure) [57] |
|---|---|---|---|---|
| Cattle | 4798 | 936 | 50 | 0.14 |
| Goats | 17,583 | 134.3 | 33 | 0.1 |
| Sheep | 58,580 | 134.3 | 33 | 0.1 |
| Camel | 22 | 720 | 50 | 0.26 |
| Horses | 218 | 620.5 | 50 | 0.26 |
| Donkeys | 1348 | 343.1 | 50 | 0.26 |
| Mules | 12 | 620.5 | 50 | 0.26 |
| Poultries | 4,827,570 | 7.04 | 99 | 0.27 |
| Layers | 265,825 | 7.04 | 99 | 0.27 |
| Mothers of Broiler | 135,923 | 7.04 | 99 | 0.27 |
| Pigeons | 16,522 | 5.0 | 30 | 0.27 |
| Rabbits | 1303 | 3.5 | 99 | 0.26 |
| Turkeys | 197,440 | 11.288 | 99 | 0.27 |
| Total annual available | | | 44,613 ton | 11,176 $Mm^3$ |

**Table 5** Annual biomass resources, biogas, heat, and electricity yields

| Item | Unit | RAW | LSW | MSW | SWW | Total |
|---|---|---|---|---|---|---|
| Amount | Ton | 119,613 | 44,613 | 40,150 | 858 | 205,234 |
| CH4 | $10^6$ $m^3$ | 25.09 | 11.17 | 1.57 | 0.015 | 37.845 |
| Heat | TJ | 812.9 | 325.1 | 50.9 | 0.494 | 1,189.4 |
| Power capacity | kW | 11,600 | 4,638 | 726 | 7.053 | 16,971 |

RAW). The proposed project is for establishing a 50 MW waste to the energy power plant. The initial investment in such projects is varying from \$25,000,000 to \$87,120,000.

It is evident from Table 5 that 148 GWh could be generated from 205 kton of biomasses, which accounts for 61.6% of Jenin's electricity consumption. The leverage cost of energy (LCOE) generated by the 40 MW capacity biomass energy system may be calculated from [70]

$$\mathrm{LOCE} = \frac{\frac{i(1+i)^n}{(1+i)^n-1}C_{\mathrm{bm}} + O_{\mathrm{bm}}}{E_{\mathrm{bm}}}, \tag{3}$$

where $C_{\mathrm{bm}}$ state for the capital cost of biomass energy systems in \$, $O_{\mathrm{bm.}}$ is the annual operation and maintenance cost of biomass energy systems including all operations of collection, handling, and pricing in \$/year, $E_{\mathrm{bm}}$ indicate to annual energy yields of biomass energy systems in kWh/year, $i$ is the interest rate and is assumed to be equal to 8%, and $n$ is the plant's lifespan and is assumed to be 30 years. Accordingly, the LCOE is ranged from ¢2.22/kWh to ¢8.71/kWh. On the other hand, it could be practical to extract biodiesel from the olive cake which is estimated at 45,576 tons. It could be extracted about 12,475 tons of biodiesel by thermochemical processes [38].

## Geothermal energy

In the absence of information about the thermal energy of water reservoirs at a depth of 2 km from the earth's surface, shallow geothermal energy which is the energy located at 5-20 m under the surface of the earth can be effectively utilized. Nassar et al. revealed that at this depth, the temperature is constant at about 16 °C all year round. It could reach in winter about 40 °C and could be cooled down in summer to 15 °C by the procedures mentioned in [71]. Following this approach, this energy can be used in winter for heating and domestic water heating and in summer for cooling. The first geothermal energy system of this type is in Ramallah at a residential building (3 floors with a total covered area is 24,000 $m^2$). This project proved to be successful as it covered about 70% of cooling and heating loads and domestic hot water load [72].

## Hybrid renewable energy (HRES)

In the present work, HOMER software was used to design a 100% renewable energy production system and to meet

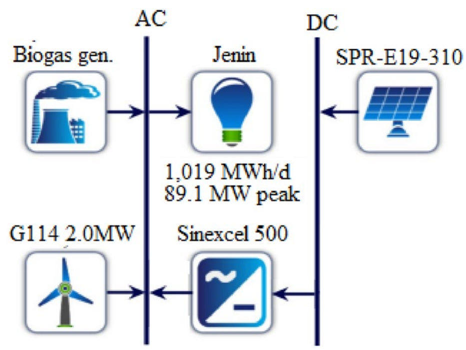



**Fig. 9** Schematic of the proposed PV/Wind/biogas HRES

100% of the electrical load of JG. The proposed HRES is schematically depicted in Fig. 9, and it consists of PV solar system, wind turbines, and a biogas-fired electrical generation system. Economic, size information, and type of the system's components are tabulated in Table 6.

The obtained results from HOMER software are presented graphically in Figs. 10, 11 and 12 for PV solar field (80 MW), wind farm (66 MW), and biogas electrical generation (50 MW), respectively. Where the operation regime and the rated power generated by each component are plotted as contours.

The results show that 100% of electrical load can be served by an energy mix of locally available renewable

**Table 6** System architecture and economic information

| Component | Type | Capacity, MW | Capital cost |
|---|---|---|---|
| Generator | Generic Biogas Genset | 50 | $56.1 M |
| PV | Sun power SPR-E19-310-COM | 80 | $127.4 M |
| Wind | Gamesa G114 2.0 MW | 66 | $125.0 M |
| System inverter | Sinexcel 500 kW | 80 | $14.4 M |
| System | | | $322.9 M |

**Fig. 10** Power generated by the PV solar system (80 MW capacity)

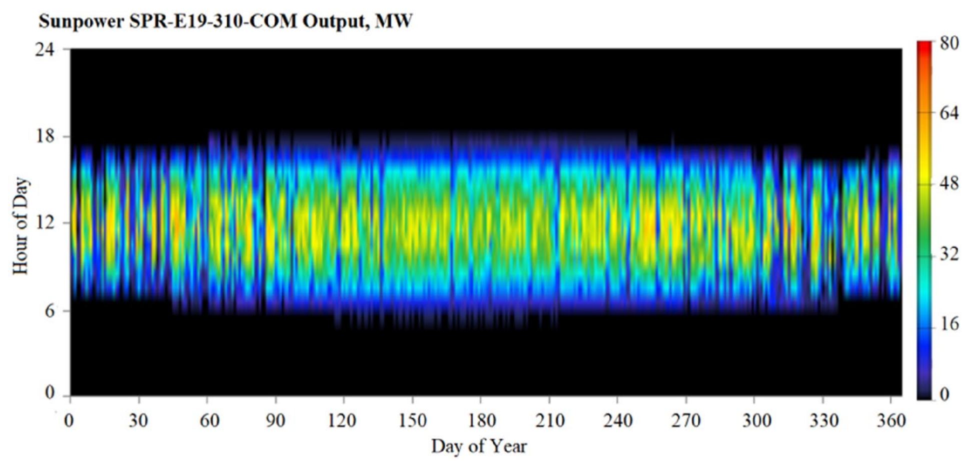
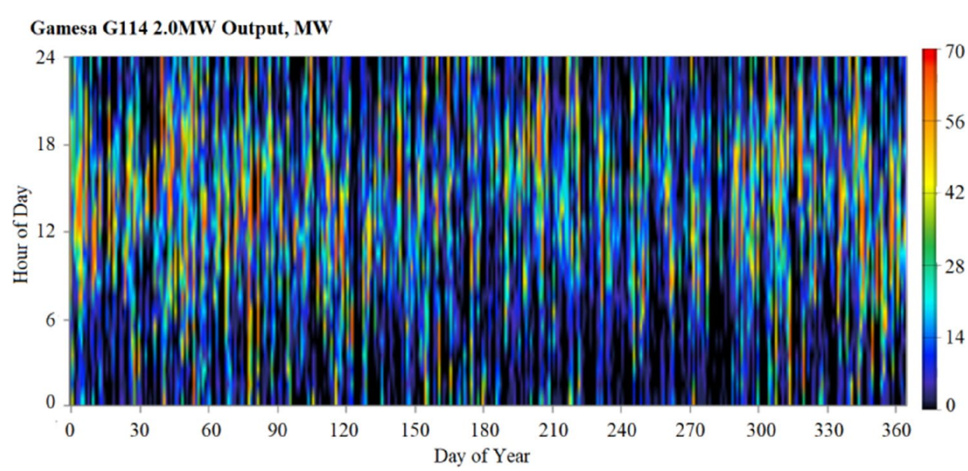



**Fig. 11** Energy generated from the wind farm (66 MW capacity)



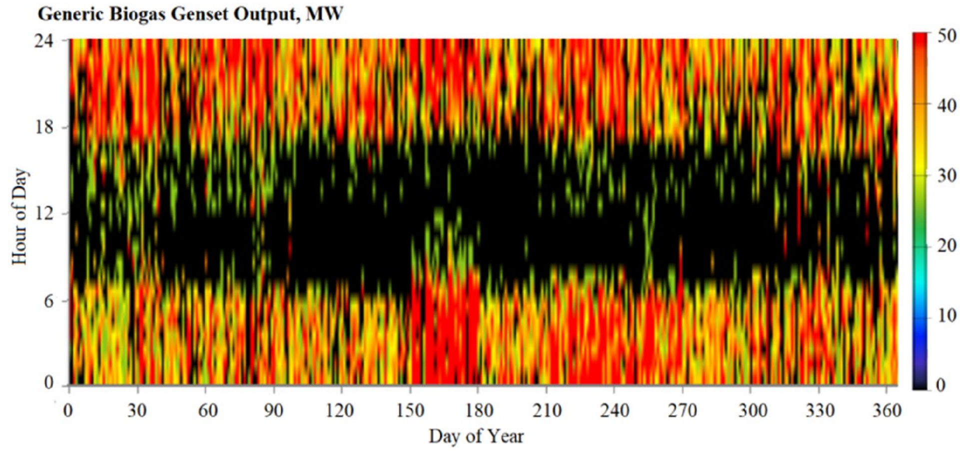



**Fig. 12** Energy generated from the biogas generator (50 MW capacity)

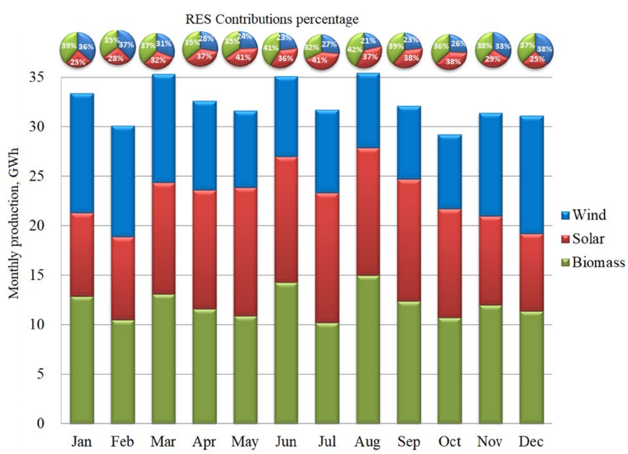



**Fig. 13** Monthly energy production and the contribution of each component in the HRES

energies. In the case of JG where the total electrical load is 371,935,041 kWh, and the hourly load is fluctuated between 20,000 kW at 2:00–4:00 and around 60,000 kW extended from 11:00 to 13:00. Regardless such a load curve is not ideal for conventional power generation stations, that is due to the large difference between the peak (90 MW) and off-peak loads (12 MW), but it is appropriate in the case of using solar energy that is due to matching the demand with supply. The proposed HRES generates 389 GWh/yr and is enough to meet 100% of the electrical demand of JG with an excess in electricity generation of about 4.57% and the unmeet electric load is about 109.6 MWh/yr which is equivalent to less than 3 h off in a year as a result of a shortage in the supply of biogas at that times; however, this shortage can be covered by used local storage of natural gas.

Figure 13 illustrates the monthly energy production and the share of each component of the HRES.

More results and data indicating what simulation parameters were taken into account are presented in Tables 8, 9 and 10 in the Appendix. While the yields of the solar field and wind farm cannot be controlled, however, biomass generation can be controlled. This advantage is essential in the case of hybrid systems where it is possible to compensate for the deficit power from solar and wind systems directly and its presence is necessary for the stability of voltages and frequency in the grid. The first estimation of the LCOE is found as \$0.313/kWh. In this regard, and to make renewable energies more competitive in the energy market, the cost of the environmental impact must be included in the economic calculations by deducting the value of the environmental damage from the aforementioned LCOE equation as done in [73].

## Conclusions

The present research introduces a methodology for simulating an (HRES) consisting of three renewable resources, i.e., solar energy, wind energy, and biomass energy. It is proved that an (HRES) consisting of 80 MW of PV solar field, 66 MW wind farm and 50 MW of biomass system will meet the electrical load of JG. The proposed Hybrid Renewable Energy System (HRES) consists of an 80 MW PV solar field, 66 MW wind farm, and 50 MW biomass system with an initial investment of \$323 M. The proposed HRES generates 389 GWh/yr and is enough to meet 100% of the electrical demand of JG (372 GWh/yr) with excess in electricity generation of about 4.57% and the unmeet electric load is about 109.6 MWh/yr which is equivalent to less than 3 h off in a year. The LCOE was found as 0.313 \$/kWh. This value of LCOE is about one and half times higher than the price of electricity provided by the Israeli company (\$0.20/kWh).

The undeniable issue is, of course, the benefits of gaining energy independence. From this point of view and due to the global energy crisis, it is justified implementation of hybrid renewable energy sources, even with no economic benefits.

## Recommendations and future visions and investigations

This topic receives great attention from specialists in Palestine as well as decision-makers from politicians, and for this reason, a research team was formed, led by the Deanship of Scientific Research at Palestine Technical University-Kadoorie (PTUK) to expand the search to figure out the effective solutions to solve the energy bottlenecks in the West Bank and Gaza Strip in particular. Research priorities in this topic have been identified in the following points:

1. Collect data on energy, and start building an energy database in Palestine.
2. Mapping the renewable energy resources' potential.
3. Finding partners and donors from universities and international research centers to contribute to the establishment of portable renewable power plants to localize alternative energy technologies in the country.
4. Encouraging and providing support to local and foreign investors to invest in renewable energy projects, including installation and production on a large scale.
5. Establishing research institutes and centers specialising in renewable energies, providing software and technologies, and holding seminars and training courses to raise awareness among residents of the importance of switching to renewable energies.
6. To improve the competitive position of renewable energy resources, the environmental factor must be included in economic calculations. The Hummer program calculates the amounts of carbon dioxide emitted by the proposed energy system but does not calculate the damage cost of the emissions.

## Appendix

See Tables 7, 8, 9 and 10.

**Table 7** Uncertainties of individual modeling steps in PV system yield prediction

| No. | Item | Uncertainty % |
|---|---|---|
| 1 | Instruments | 2.76 |
| 2 | POA | 6.0 |
| 3 | Effective irradiance | 4.0 |
| Solar radiation resource | | 7.7 |
| 4 | STC | 3.5 |
| 5 | Module technology | 2.13 |
| PV module characteristics | | 4.1 |
| 6 | Inverter | 1.6 |
| 7 | Transformer | 1.0 |
| 8 | DC cabling | 0.5 |
| 9 | Losses | 1.5 |
| 10 | Degradation | 0.4 |
| System output | | 2.5 |
| Total uncertainty | | 9.1 |

**Table 8** Generic biogas Genset electrical, fuel, and statistics summary

| Metric | Value | Units |
|---|---|---|
| Power capacity | 50 | MW |
| Electrical productivity | 145 | GWh/yr |
| Mean electrical output | 16.6 | MW |
| Minimum electrical output | 0 | MW |
| Maximum electrical output | 50 | MW |
| Fuel consumption | 303,859 | tons/yr |
| Specific fuel consumption | 2.12 | kg/kWh |
| Mean electrical efficiency | 30.8 | % |
| Hours of operation | 4,632 | h/yr |
| Number of starts | 808 | starts/yr |
| Lifetime | 30 | years |
| Fixed generation cost | 4.41 | $/hr |
| Variable operation cost | 5.0 | $/MWh [74] |
| Capital cost | 56,060,000 | $ |
| Carbon dioxide emission | 1670 | ton/yr |

**Table 9** PV solar field electrical and statistics summary

| Metric | Value | Units |
|---|---|---|
| PV module type | Sun power SPR-E19-310-COM | |
| Capacity | 310 | W |
| Tilt and azimuth angles | 20°, south facing | |
| Power capacity | 80 | MW |
| Electrical productivity | 131 | GWh/yr |
| Mean electrical output | 15.3 | MW |
| Minimum electrical output | 0 | MW |
| Maximum electrical output | 80 | MW |
| Capacity factor | 18.7 | % |
| Specific yield | 1,638 | kWh/kW |
| Hours of operation | 4,367 | h/yr |
| PV Penetration | 56.6 | % |
| Efficiency | 19.1 | % |
| Lifetime | 30 | years |
| Area land | 1,401,864 | $m^2$ |
| Operation and maintenance cost | 17 | $/kW/yr [75] |
| Capital cost | 127,385,192 | $ |

**Table 10** Wind farm electrical and statistics summary

| Metric | Value | Units |
|---|---|---|
| Wind turbine type | Gamesa G114 2.0 MW | |
| Capacity | 2.0 | MW |
| Rotor diameter | 114 | m |
| Shear coefficient | 0.14 | |
| Hub height, | 100 | m |
| Power capacity | 66 | MW |
| Number of turbines on the farm | 33 | |
| Electrical productivity | 119 | GWh/yr |
| Mean electrical output | 13.1 | MW |
| Minimum electrical output | 0 | MW |
| Maximum electrical output | 66 | MW |
| Capacity factor | 19.8 | % |
| Specific yield | 1803 | kWh/kW |
| Hours of operation | 6762 | h/yr |
| PV Penetration | 30.1 | % |
| Lifetime | 30 | years |
| Area land | 16,005,000 | $m^2$ |
| Operation and maintenance cost | 35 | $/kW/yr [74] |
| Capital cost | 125,034,530 | $ |

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**Data availability** The original contributions presented in the study are included in the article/Supplementary Material, and further inquiries can be directed to the corresponding author. And all data and information used in this paper were properly cited and available in the library of Google scholar.

## Declarations

**Conflict of interest** The authors have no relevant financial or non-financial interests to disclose.

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