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Optimal design and analysis of grid-connected photovoltaic under different tracking systems using HOMER

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A B S T R A C T

This research contributes to the ongoing discussions about the grid-connected solar photovoltaic (PV) systems and draws attention to the optimal design by considering various PV array tracking systems towards enhancing the power generation. The PV tracking system configurations considered in this study include horizontal-axis (monthly adjustment, weekly adjustment, daily adjustment, continuous adjustment), vertical-axis (continuous adjustment), and a two-axis tracking system. HOMER (Hybrid Optimization of Multiple Energy Resources) software is employed whereas the actual data required by the model have been collected in Makkah, Saudi Arabia.

The results show that the two-axis tracker can produce 34% more power than the fixed system, while the vertical axis tracker with continuous adjustment was able to generate up to 20% more power than the fixed system. Horizontal tracker with continuous adjustment shows the highest net present cost (NPC) and the highest levelized cost of energy (LCOE), with a high penetration of solar energy to the grid. For the case of Makkah, the vertical axis tracker with continuous adjustment is the best option as it has low LCOE and NPC values with a positive return on investment (ROI) as well as high renewable energy penetration to the grid, which enhances its viability for a utility-size solar PV grid-connected system.

1. Introduction

Presently, most of the energy supplied globally is generated from fossil fuels such as coal, oil, and natural gas. The major disadvantages of the fossil fuel sources are their fluctuating prices, environmental pollution, and the fact that they are finite resources. In this context, renewable energy sources (RES) are promising to take a significant share in the energy sector and they are considered a viable option for integration with conventional fossil fuel power plants. Currently, more than 24% of power globally is generated by RES, as shown in Fig. 1. RES including solar, wind, biomass, and geothermal are clean and easily replenished sources. In 2016, more than 170 countries adopted at least one type of RES target, an upward trend from only 43 countries in 2005 [1]. Among the RES technologies, solar energy technologies have shown a significant advancement and maturity for power generation. Solar photovoltaic (PV) technology, which directly converts the sun irradiation into electricity, is one of the fastest growing RES technologies worldwide. Recently, the solar PV modules' prices have dropped by 80% since 2009 and are anticipated to keep falling [2].

Solar PV technologies have improved in efficiency whereas their manufacturing costs have declined over the past few years. In contrast to the concentrated solar thermal technology, PV panels work in the presence of both direct and diffuse solar irradiations.

The integration of fossil fuels with RES produces a hybrid electrical system that overcomes the major limitations of solar energy, which are its intermittency and the fluctuating energy quantity. Such hybrid schemes could deliver a more reliable, sustainable, and environmentally friendly system. For the last 15 years, the deployment of grid-connected PV surpasses the off-grid installation of PV worldwide, as shown in Fig. 2 [3]. The exploitation of utility-size grid-connected solar PV has proven its advantages and has gained favor where vast areas are accessible and where significant amount of solar irradiation is available. This research focuses on optimal design of grid-connected solar PV and studies different tracking systems to compare their technical and economic feasibility. It aims at designing a system that requires the lowest investment among the alternatives available while providing a highly efficient solar PV system. As per the authors' knowledge, this techno-economic investigation of the tracking systems with different time adjustment for a grid-connected configuration, represents an original contribution.

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Nomenclature

Greek letters

α	temperature coefficient of power, %/°C

Symbols

C	cost, USD
CRF	capacity recovery factor
f	derating factor, %
G	solar irradiation, kW/m^2
GHI	global solar irradiation, kW/m^2
i	annual real interest rate, %
N	project lifetime, year
P	generated power, kW
R	load, kWh/year
T	temperature, °C
Y	rated capacity of PV, kW

Abbreviations

AC	alternating current
DC	direct current
ECRA	Electricity and Cogeneration Regulatory Authority
FT	fixed system with no tracking
GCC	Gulf Cooperation Council
GHI	global horizon irradiance
HCA	horizontal-axis with continuous adjustment
HDA	horizontal-axis with daily adjustment
HMA	horizontal-axis with monthly adjustment
HOMER	hybrid optimization of multiple energy resources
HWA	horizontal-axis with weekly adjustment
K.A.Care	King Abdullah City for Atomic and Renewable Energy
LCOE	levelized cost of energy
NPC	net present cost
NREL	National Renewable Energy Laboratory
PV	solar photovoltaic
REFIT	renewable energy feed-in tariff
RES	renewable energy sources
ROI	return on investment
SEC	Saudi Electricity Company
TA	two-axis
VCA	vertical-axis with continuous adjustment

Subscript

ann,tot	total annualized
c	cell
cap	system capital cost
cap,ref	reference system capital cost
i,ref	reference system annual cash
p	power
prim	primary
proj	project
STC	standard test condition
T	current time step
tot,grid,sales	total grid sales

Superscript

N	project lifetime, year

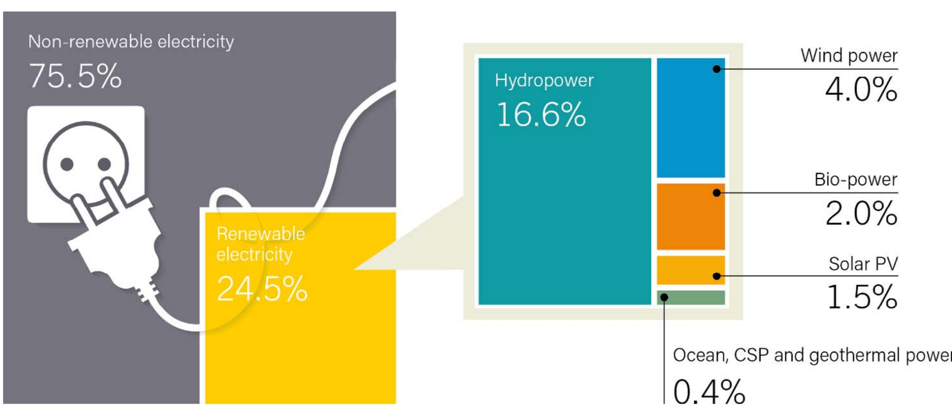

Fig. 1. Renewable energy share in global power production by the end of 2016 [1].

Oil-dependent countries including Saudi Arabia, which is a major oil producer and exporter, and the country with highest oil consumption in the Middle East, have an arduous task ahead concerning energy production and consumption [4]. Nowadays, 100% of the power in Saudi Arabia is generated from fossil fuels, as shown in Fig. 3. Saudi Arabia consumes more than 3 million barrels/day of oil, primarily for power generation, water desalination, and transportation [5]. The growing power demand is burdening the country, as generating more power means burning more fossil fuel. Recently, the Electricity and Cogeneration Regulatory Authority (ECRA) highlighted the power gap as high as 25% between the supply by the Saudi Electricity Company's (SEC), the main electricity provider, and the peak loads in central and southern provinces [6]. Furthermore, according to The World Bank, the CO_2 emissions in Saudi Arabia were around 18.1 metric tons per capita in 2013, which places it in the top 10 countries in CO_2 emissions worldwide [7].

The prolonged hot weather during summer is causing a significant usage of air conditioning, which consumes more than 60% of the total power generated in the country [8]. To tackle the high power consumption issue, several measures have already been taken by the decision makers, including the establishment of the Saudi Energy Efficiency Centre in 2010 to publicize the rationalization awareness and to boost power consumption efficiency, in order to preserve the national wealth of energy resources [9]. Furthermore, the King Abdullah City for Atomic and Renewable Energy (K.A.CARE) was established, to improve the diversification of energy resources. In June 2016, the government removed subsidies for power generation and made a new adjustment to the consumption tariffs, which caused an increase in the cost of energy of more than 60% in some service categories [8]. Such policy measures were intended to encourage commercial and industrial solar energy applications in the country. Currently, Saudi Arabia plans to produce 9.5 gigawatts from renewables, mainly solar and wind power, by 2023

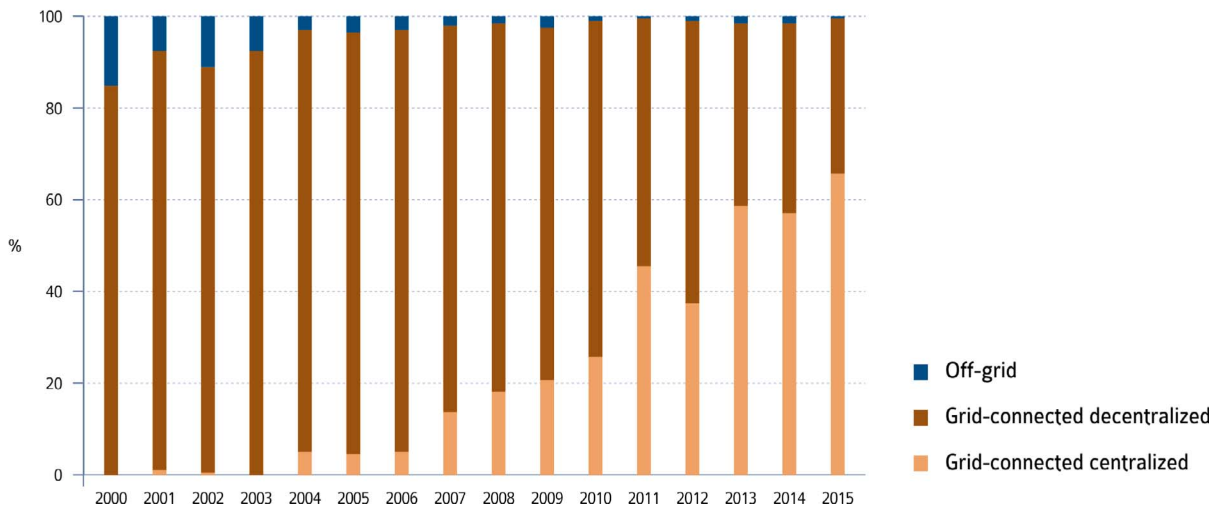

Fig. 2. Share of grid-connected and off-grid installations 2000–2015 [3].

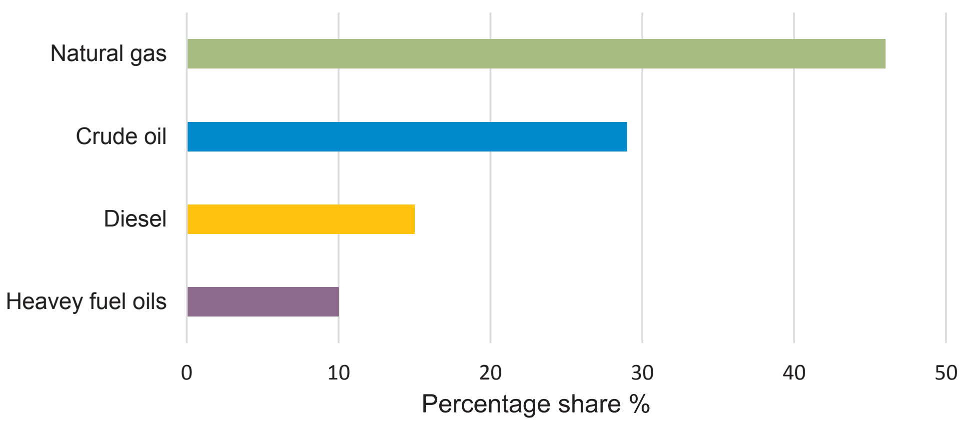

Fig. 3. Fuel types used in electricity production in Saudi Arabia in 2013 in percentage [6].

as a part of the Kingdom's 2030 vision [10].

Considering such relevance of the grid-connected solar energy technologies, the objective of this paper is to examine the grid-connected solar PV systems propped by different tracking systems, and particularly to examine their performance under different time adjustments. As per the authors' knowledge, this is the first study examining different tracking designs for a grid-connected configuration with their impact on the system cost. Furthermore, this is an original techno-economic study of solar PV tracking systems in Gulf Cooperation Council countries (i.e. Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates) to date, which entailed a detailed investigation of the local conditions. This objective requires a comprehensive investigation, and the technologies examined have a high potential deployment in this region.

This paper is organized as follows. Section 2 reviews the related studies about grid-connected PV and tracking systems. In Section 3, the problem definition and the case study are presented. Then in Section 4, the proposed system designs and the associated model inputs are defined. The results and discussion of various cases considering tracking designs are presented in Section 5. Finally, the conclusion and future works associated with this research are presented in Section 6.

2. Literature review

Many research papers studied the techno-economics of PV systems based on off-grid [11–23] or grid-connected settings [24–32]. The grid-connected systems are intended to supply power generated by RES into the electric grid. Such schemes could be in a distributed form, serving a particular grid-connected client, or in a centralized form, delivering power into a transmission grid. Hafez in [32] studied different configurations of hybrid renewable energy systems including diesel only, fully RES, diesel-RES mixed and RES-grid-connected configuration. Using the hybrid optimization of multiple energy resources (HOMER) software, the load applied was a hypothetical rural community, while the solar data was derived from National Aeronautics and Space Administration (NASA) surface metrology database. The results showed that diesel-RES mixed configuration has the lowest net present cost (NPC), while the fully RES has the highest NPC with no carbon emissions. A hybrid RES grid-connected system was found to be the most economical option due to the low capital cost. Furthermore, a break-even grid extension distance from the microgrid was analyzed.

Anwari and Ayong in [24] studied the technical feasibility of off-grid PV that generated 2.5% of load requirement of Makkah city in Saudi Arabia based on solar irradiance using HOMER software. The load profile with random variability factors was assumed based on the load pattern in Makkah with no grid connection consideration. In [25], they applied grid-connected solar PV to the same case. Similarly, Adaramola examined the feasibility of grid-connected solar PV in Jos, Nigeria, investigating the technical and economic performance of the system [26]. The load profile was assumed based on the pattern of the energy consumption in Jos. He concluded that the solar PV system could provide for around 40% of the annual electricity consumption, whereas, aside from the amount of solar irradiation, the initial cost of the scheme plays a significant role in electricity price. Tomar and Tiwari in [27] studied demand-side management to obtain an optimal design of solar PV system for a decentralized application in New Delhi, India. They concluded that a grid-connected solar PV system without battery storage is a technically and economically viable option for decentralized applications. Mondal et al. [28] examined the economic feasibility of grid-connected solar PV for Bangladesh employing a proposed 1 MW solar PV system. All sites showed favorable condition for development of the proposed solar PV system. Liu et al. [29] simulated and optimized a grid-connected PV system of residential power supply in Queensland, Australia. It is found that the PV system is an effective way to decrease electricity bills and mitigate CO_2 emissions. Raturi et al. [30] described the current status of grid-connected PV systems in the Pacific region and reviewed some challenges associated with the power utilities which are completely dependent on diesel generators and hydropower. The results obtained that both grid-connected and stand-alone solar PV presented economically attractive to tackle these challenges. Kim et al. examined hybrid PV-wind-battery systems by simulating a system composed of a renewable energy grid system and a diesel generator on Jeju Island in South Korea [33]. This study found that the grid-connected PV-wind-battery hybrid system is the most economically feasible system. Furthermore, comprehensive reviews of different aspects of grid-connected PV systems, along with highlights on technical and economic constraints that may hinder the solar energy projects, were provided in [34,35].

In promoting RES, the renewable energy feed-in tariff (REFIT) mechanism has been applied the most extensively and it has proven to be an efficient system offering substantial benefits to both RES project developers and consumers [36]. REFIT has prevailed as a fruitful policy approach to spur renewable energy penetrations, which obligates the public power entities to purchase the power generated from RES. Lau in [31] analyzed the effects of such policy and economic factors on grid-connected PV systems in Malaysian residential sector. The effect of varying interest rates, electricity tariffs, and the carbon tax was discussed. The grid-connected system with no battery showed to be the most feasible alternative, as introducing a battery increases the system's NPC. As of 2016, more than 100 countries and provinces enacted feed-in-tariff policies [1]. The REFIT is considered to be the most commonly adopted regulatory mechanism to prompt RES.

The performance of solar panels is primarily dependent on the amount solar irradiation received. Hence, a mechanical system that tracks the sunlight and enables orienting the panel towards being perpendicular to the light beam leads to capturing more solar irradiation, which accordingly advances the system performance. A tracking system for a PV array can increase the array's annual energy production up to 27% using a single-axis tracker and 40% for dual-axis trackers [37–39]. A single-axis tracker adjusts either the azimuth or the tilt angle, while dual-axis tracking can adjust both angles. The tilt angle is the vertical angle between the horizontal plane and the solar panel surface (typically towards the south if PV site located in north hemisphere). The azimuth angle is the deviation angle between the surface and the south direction horizontally, as illustrated in Fig. 4.

Typically, PV panels are installed with fixed tilt and no tracking system, as in the cases studied in [26,41–47]. Nevertheless, single-axis and dual-axis trackers have recently undergone intense research. In addition to the daytime movement of the sun rays from morning to evening, their direction also varies across the seasons throughout the year.

Compared to fixed systems, the advantage of the tracking systems is the significant boost in power production. In high irradiation areas, one-axis tracking has dominated for utility-scale PV systems, with benefits greater than the costs [48]. Lazaroiu et al. [49] examined the daily energy production of a fixed system and the sun-tracking PV systems and found that sun tracker systems generated 12–20% more power than the fixed system. Based on both technical and economic criteria, Alexandru [50] determined that a single axis tracking system is preferable to dual-axis tracking for the area of Brasov, Romania. Mehrtash et al. [51] investigated the performance of solar tracking PV systems in Toronto, Canada with four different tracking systems: fixed tilted, fixed horizontal, single-axis and dual-axis tracking. The study showed that dual-axis tracking received 33% more irradiation and generated 36% more electricity than the tilted system.

A review of sun-tracking methods by Mousazadeh et al. [52] concluded that using two-axis sun-trackers can increase the energy production by 30–40% yearly. Eke and Senturk in [53] compared double-axis sun tracking versus a fixed PV system and found that 30.79% more electricity is obtained with double-axis sun-tracking. Similarly, Ismail et al. [54] found that dual axis tracker achieved 20.4% more in annual energy production compared to a fixed system. Salah [55] studied four tracking systems including dual-axis, one axis vertical, one axis east-west and one axis north-south. The results revealed that each of the four trackers was superior to the fixed system. The electrical power gain was 44%, 38%, 34% and 16% for the two axes, east-west, vertical and north-south tracking, respectively. The above-mentioned studies reveal that solar PV tracking systems are superior to the fixed systems when it comes to power generation. However, there is no study investigating the techno-economic aspects of different PV tracking system configurations with different time adjustments, including fixed system, horizontal-axis, vertical-axis, and two-axis for a grid-connected solar PV.

3. Problem definition

The techno-economic assessment of energy systems could be carried out using reliable and advanced commercial simulation tools as an alternative to the complex and lengthy algorithms and to the costly physical experiments. Currently, there exist several software to design, optimize and simulate RES, primarily aiming at technical and economic assessment. HOMER, RETScreen, PVSyst, Hybrid2, iHOGA, and TRNSYS are among the most popular and the most frequently reported software tools in the literature. Due to the nature of the problem, which includes 1-h time-step data of load profile and air temperature, HOMER has been selected for this study, as it is superior to other software in handling this type of input. Moreover, HOMER demonstrates high capability to handle different simulation scenarios, including various tracking schemes, and to perform optimization and sensitivity analysis. Also, it is user-friendly and offers powerful graphical presentations. Computer tools used for the integration of renewable energy into various energy systems with different objectives were analyzed and compared by Connoly et al. [56]. According to a recent study of 19 software associated with RES sizing and planning, Sinha and Chandel concluded that HOMER, developed by the National Renewable Energy Laboratory (NREL), is the easiest to use and the fastest in evaluating the RES [57,58]. Moreover, Bahramara et al. presented a comprehensive review of papers which used HOMER exclusively for optimal planning in the area of RES. The study showed that HOMER software is the most popular tool considered by many researchers and that it has been applied widely in the developing countries [59].

The primary economic metrics used to rank various energy system configurations are the NPC and the levelized cost of energy (LCOE). The NPC computes the present cost of installation and operation of the entire system over the project lifetime minus the present revenues, and it can be expressed by Eq. (1), whereas the LCOE calculates the average cost per kWh of electrical energy in the system and is calculated using

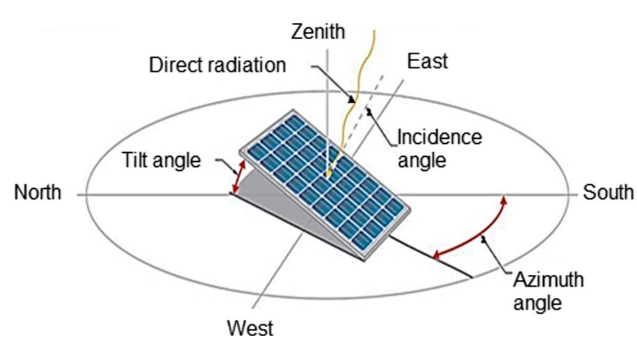

Fig. 4. The tilt and azimuth angles of the solar panel [40].

Eq. (2).

$$NPC = \frac{C_{ann,tot}}{CRF(i,N)} \quad (1)$$

where $C_{ann,tot}$ is the total annualized cost, i is the annual interest rate, N is the project lifetime, and CRF is the capacity recovery factor, given by $CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N-1}$

$$LCOE(\text{"\$"/kWh}) = \frac{C_{ann,tot}}{R_{prim} + R_{tot,grid,sales}} \quad (2)$$

where R_{prim} is the primary load (kWh/year) and $R_{tot,grid,sales}$ is the total grid sales (kWh/year).

When making such important decisions, alternative economic performance measures could be considered. Along with NPV and LCOE, the return on investment (ROI) represents the amount of return on an investment relative to a reference system. HOMER calculates ROI using Eq. (3):

$$ROI = \frac{\sum_{i=0}^{N} C_{i,ref} - C_i}{N(C_{cap} - C_{cap,ref})} \quad (3)$$

where:

- $C_{i,ref}$ = reference system nominal annual cash flow
- C_i = current system nominal annual cash flow
- C_{cap} = current system capital cost
- $C_{cap,ref}$ = reference system capital cost

Beyond the original approach presented in this research, the case of the Makkah, Saudi Arabia is investigated as a case study. Makkah is the capital city of the western region with the highest number of consumers (more than 2.7 million), and it had a maximum energy sale of 84,264,000 MWh in 2014 [6]. Makkah has an extremely hot summer season and it hosts millions of visitors every year during various religious occasions. Consequently, the power grid experiences a high-power consumption, mainly due to air-conditioning. A recent study by Al Garni and Awasthi in [60] investigated the most suitable sites towards deploying a utility-size solar PV in Saudi Arabia. This study found Makkah city as a highly suitable site for such a project considering several technical and economic factors.

A significant drawback of the solar energy lies in its unpredictable nature, as it depends on weather conditions. Nevertheless, the high demand in Makkah quite often coincides with the high solar irradiation, particularly during the summer season. Fig. 5 depicts the real load profile data for the period 2011–2015 and the monthly average global horizon irradiance (GHI) for the period 1994–2012 on the monthly average basis. This indicates that solar energy technologies may be able provide an adequate alternative source of energy. The solar power is a potential supplement to the primary utility's generation to cope with the massive load.

One of the key factors in solar PV performance is the angle between the sun rays and the solar PV panels. Accordingly, the main objectives of this research are as follows:

- To examine different solar PV tracking system configurations with different time adjustments, including horizontal-axis, vertical-axis, and two-axis systems by studying their impact on the system cost and power generation.
- To design an optimal solar PV grid-connected system based on realistic key inputs including metrological data, user profile data, and economic factors.

4. System under consideration

To achieve the above objectives simulation and optimization processes are used. The major inputs for the simulation and optimization model consist of the key factors in the performance of a PV system. The model inputs are electrical load, solar irradiation, air temperature, components cost, and energy prices. In contrast to studies [24] and [36], real-data including metrological data, load profile, and the technical and economic characteristics of the equipment are used in this research. Fig. 6 shows the major research steps. In previous work [61] the authors have presented a preliminary analysis of the model presented in this manuscript considering different costs inputs as well as different technical and economic measures. In this paper, we extend this work by adding a comprehensive analysis to each tracking system performance under feed-in-tariff mechanism with a detailed investigation of the local conditions. Moreover, an additional economic measure, ROI, has been examined and compared among different tracking design. The following sub-sections describe the system design components with their specifications applied in this study.

4.1. Model inputs

4.1.1. Metrological data

Solar irradiation and the ambient temperature of the PV array affect the amount of energy that a PV system generates. Accordingly, HOMER uses the monthly average global horizon irradiance and the monthly average temperature among its inputs. These inputs are defined in the HOMER resources, and their effects on the output performance of the PV system are described. The following points give more detail about the data used in this study for these two variables:

- **The solar irradiation:** the monthly average GHI of Makkah (Latitude 21.42 N, Longitude 39.82 E) is downloaded from K.A.CARE. It is based on GeoModel Solar for the period 1994 – 2012 with 3 km resolution. An extensive comparison study for 18

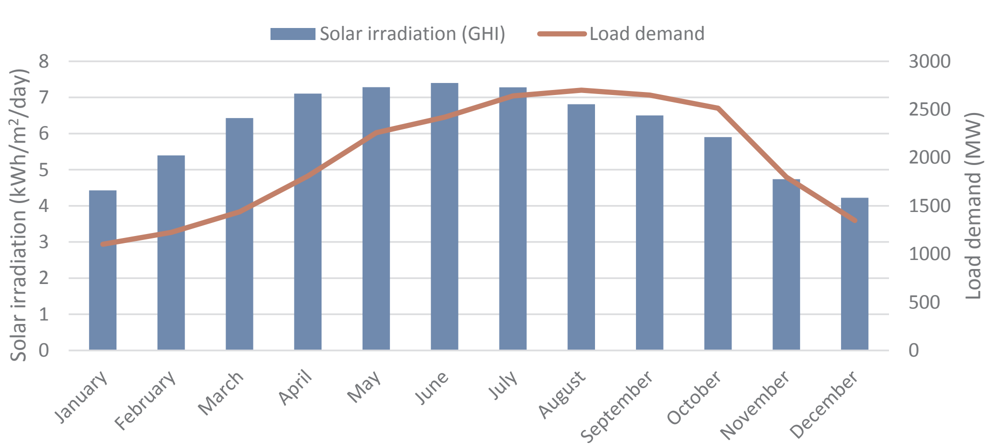

Fig. 5. The relation between load demand and global horizontal irradiation in Makkah City.

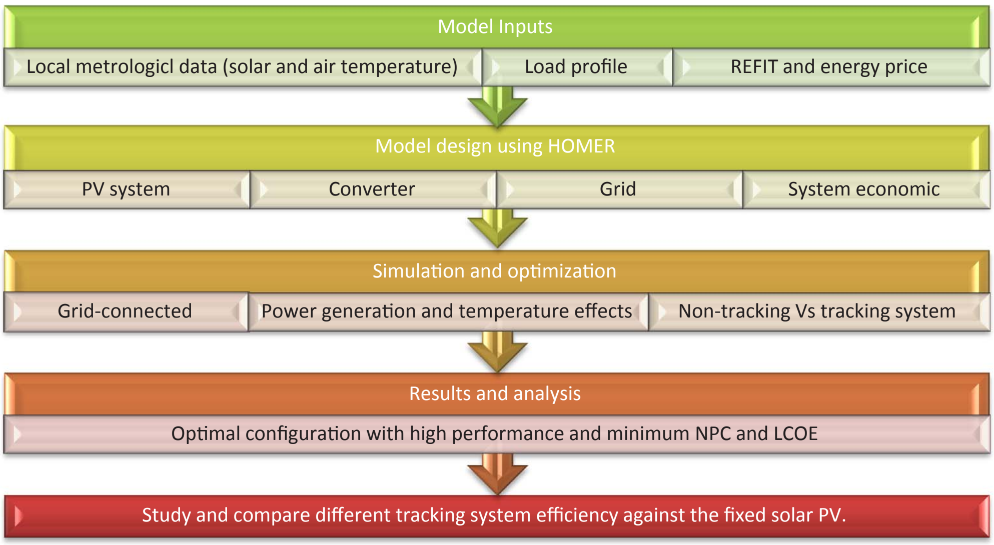

Fig. 6. Proposed steps for optimal sizing of PV grid connected system.

validation locations in Europe and the Mediterranean region, authored by Ineichen, concluded that Geomodel data has the lowest overall bias [62]. The solar irradiation ranges between 4.22 kWh/m^2/day and 7.4 kWh/m^2/day, whereas the annual average solar irradiation for this region is 6 kWh/m^2/day as depicted in Fig. 7. From March to September, the GHI rises above the average, with a peak in June. The remaining months particularly January, December, and November have relatively low solar irradiation.

- **The air temperature:** the monthly average temperature for years 2011–2015 using a 1-h time step, is depicted in Fig. 8. The average annual temperature is 31 °C, and the long summer season with even higher temperatures is from May until September. This ambient temperature profile will be considered in determining the PV power efficiency, as HOMER software can calculate the power output of a PV array utilizing the cell temperature in each time step. Fig. 9 shows the temperature data frequency distribution with a normal shape.

4.1.2. Load profile

From the demand perspective, the load profile of any study area is the most significant factor in the optimization process. The load profile is critical for accurately designing an optimal system, which means to satisfy the power demand at any given time and avoid extra costs due to overdesign. Compared to other regions in Saudi Arabia, western region has the highest number of consumers and the highest energy sales [6]. The electricity demand of Makkah has significant fluctuations due to several factors including weather variations - an extremely hot summer, religious events such as the month of fasting (Ramadan), and pilgrimage (Hajj), and other special occasions (National day, Eids, etc.) [25]. Fig. 10 shows the yearly average electrical load profile for years 2011 to 2015 in 1-h time step size.

Fig. 11 illustrates the monthly average load profile with a peak demand starting in April, continuing during summer season and declining in November. This is mainly due to the overlap of the summer and the Holy Mosque visitors' period. The daily average power consumption is 47,752 MWh/d with a peak of 3041 MW.

The histogram in Fig. 12 shows a bimodal distribution with two relative peaks of power demand (1200 MW and 2600 MW). The relative frequency of load consumption reveals that the highest frequency is between 2000 and 3000 MW yearly. Another peak is between 1000 and 2000 MW with lower frequency. This indicates that different customers utilized a different distribution of power consumption throughout the year.

4.1.3. Grid and renewable energy feed-in-tariff

The utility grid is the main power supplier, whereas the solar PV system runs in daytime only. However, if the power generated by the solar PV exceeds the primary load demand, the surplus electricity is sold to the grid. Several studies have shown that utilizing the excess energy in this way can significantly reduce the LCOE [63]. The REFIT is a long-term policy agreement with the RES provider to pay for the electricity that the RES system feeds into the grid. Recently, based on an

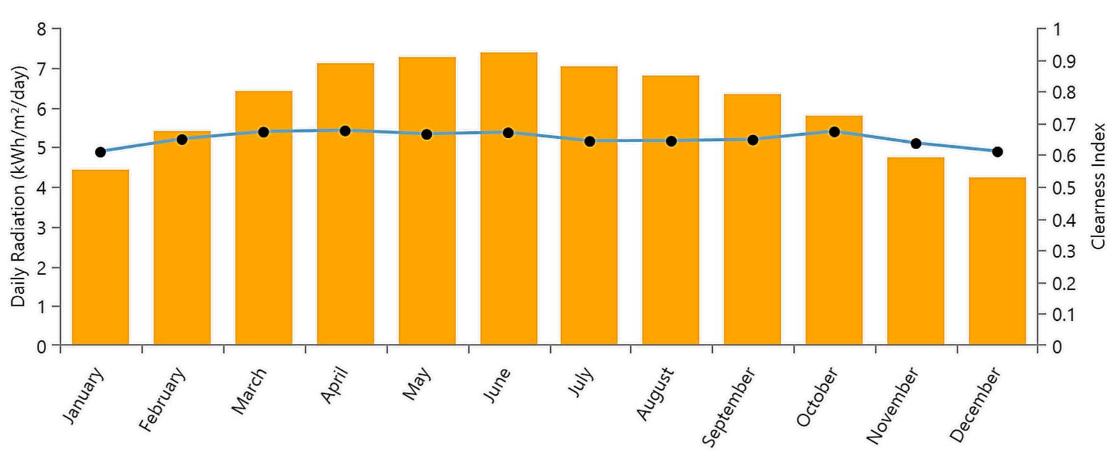

Fig. 7. The monthly average GHI in Makkah.

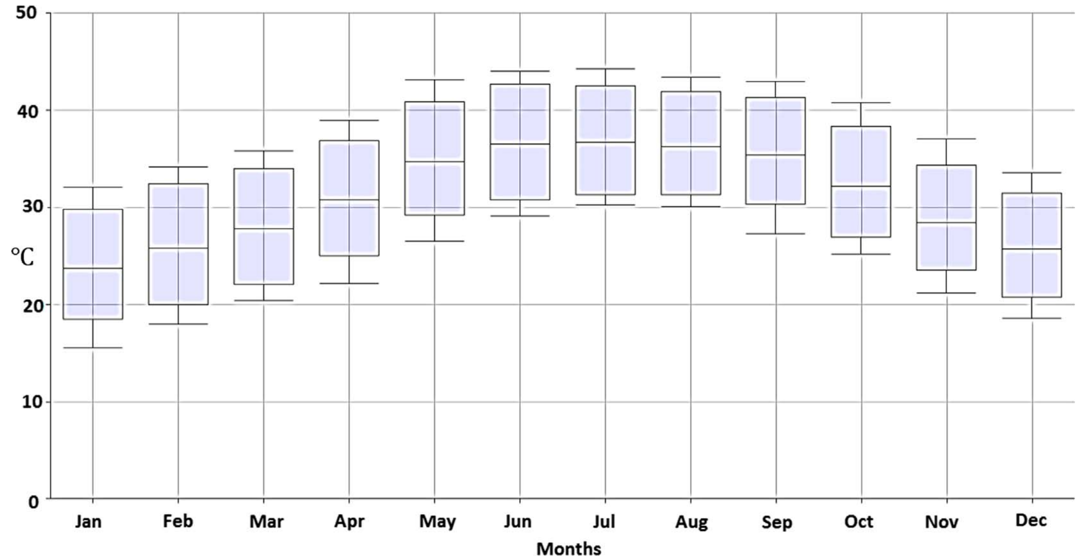

Fig. 8. The monthly average temperature.

assessment of REFIT and their applications in Europe, Asia, and Africa, Ramil et al. in [36] concluded that applying fixed REFIT in Saudi Arabia is likely to accelerate the development of its renewable energy sector. Such fixed pricing scheme is market independent, which neglects inflation and is not affected by the fossil fuel prices. Accordingly, the residential rate in Saudi Arabia (see Table 1) is utilized to design a scheduling rate that permits fixed prices at each time of day and month as presented in Fig. 13.

Fig. 13 shows the daily grid scheduled rates divided into five intervals based on the peak load period, where each column presents the daily hours starting at 00:00 [25]. The rates include off-peak, shoulder and peak hours whereas their prices are \$0.016/kWh, \$0.027/kWh, and \$0.040/kWh respectively, as shown in Fig. 14. As a result, the buying/selling of power from/to the grid at a fixed REFIT scheme is possible.

4.2. Model design of solar PV grid-connected using HOMER

The design of the system under consideration comprises four components: solar PV array, direct current (DC) to alternating current (AC) converter, grid system, and primary load as presented in Fig. 15. Grid-connected PV systems require an inverter to adapt the DC generated by the PV array and supply it to the load side. Since this system has no batteries or external generator, the utility grid will be the main power supplier to the load.

4.2.1. PV modules

A PV module is a RES integrated into the system, which supplies renewable electricity to the DC line. The size of a PV module depends on the system constraints, including the unmet load permission and the size of other renewable fractions contributing to the system. In this study, the PV system should be sized to deliver the required peak load demand, and this determines the output power requirement of a PV panel system. The output power of a PV system can be calculated using Eq. (3) [64].

$$P_{PV} = Y_{PV} * f_{PV}\left(\frac{\overline{G}_T}{\overline{G}_{T,STC}}\right)[1 + \alpha_P(T_c - T_{c,STC})] \tag{3}$$

where:

- P_{PV} = is the generated power from PV system

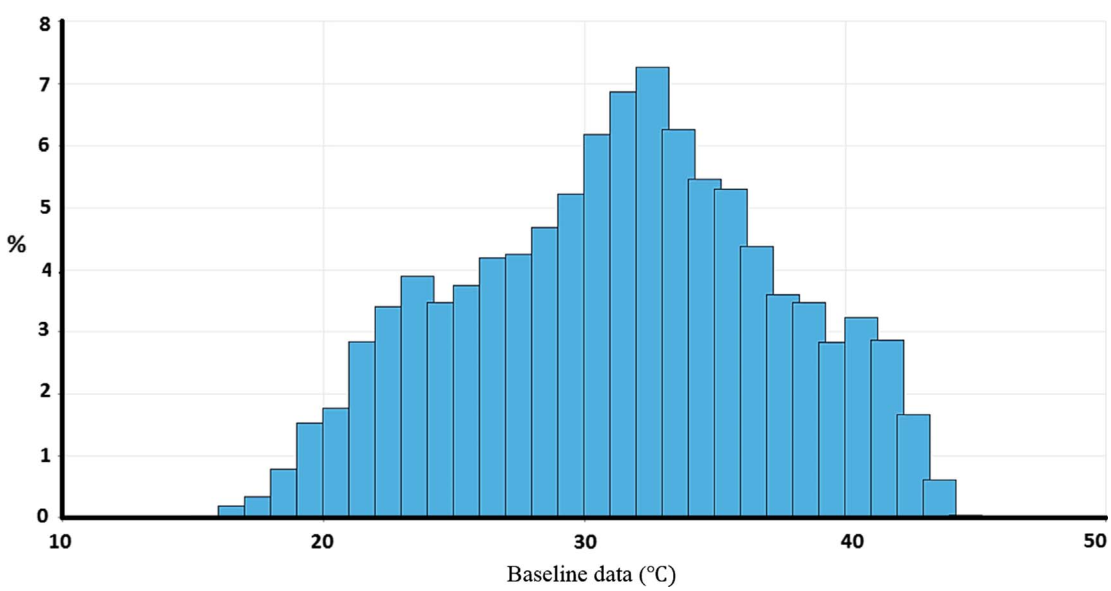

Fig. 9. Histogram graph of temperature data of Makkah.

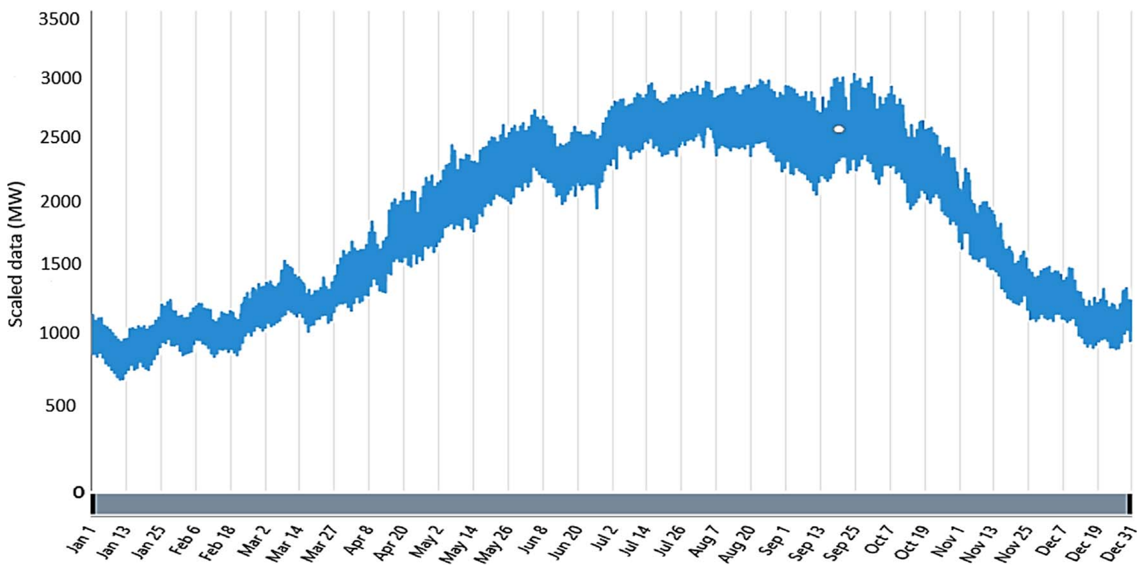

Fig. 10. The annual average electrical load of Makkah.

- Y_{PV} = is the rated capacity of the PV array [kW]
- f_{PV} = is the derating factor [%]
- $\overline{G}_T$ = is the solar irradiation on the PV [kW/m^2]
- $\overline{G}_{T,STC}$ = is the incident irradiation at standard test conditions [1kW/m^2]
- α_P = is the temperature coefficient of power [%/°C]
- T_c = is the PV cell temperature [°C]
- $T_{c,STC}$ = is the PV temperature under standard test conditions [25 °C]

As illustrated in Eq. (3), the power generated from a PV system is influenced by several factors including the PV cell temperature and the amount of solar irradiation. Table 2 presents the financial and technical input data of the PV and inverter types.

4.2.2. Solar PV tracking system designs

Nowadays, most of the solar PV arrays are installed on a fixed mounted system, where PV panels may be installed with a fixed tilt angle. Such fixed systems, where panels are installed at a fixed slope and azimuth, have the advantages of simplicity and low-cost. However, they have a significant deficiency in receiving adequate solar irradiation, since the sun moves throughout the day and changes its orbit seasonally. Therefore, a fixed system with no tracking (FT) is considered the base case in this research. Tracking systems are categorized according to their number of rotation axes as shown in Fig. 16. The following six tracking systems are considered [64]:

1. **Horizontal-axis with monthly adjustment (HMA):** the rotation axis is around the horizontal (east-west), whereas the tilt angle is adjusted each month to have a close-to-perpendicular angle between sun rays and panels at noon time.
2. **Horizontal-axis with weekly adjustment (HWA):** the rotation is around the horizontal, whereas the tilt angle is adjusted every week.
3. **Horizontal-axis with daily adjustment (HDA):** the rotation is around the horizontal, whereas the tilt angle is adjusted each day.
4. **Horizontal-axis with continuous adjustment (HCA):** the rotation of HCA is around the horizontal, while the tilt angle is adjusted continuously.
5. **Vertical-axis with continuous adjustment (VCA):** the system rotates continuously around the vertical (north-south) axis, whereas the tilt is fixed.

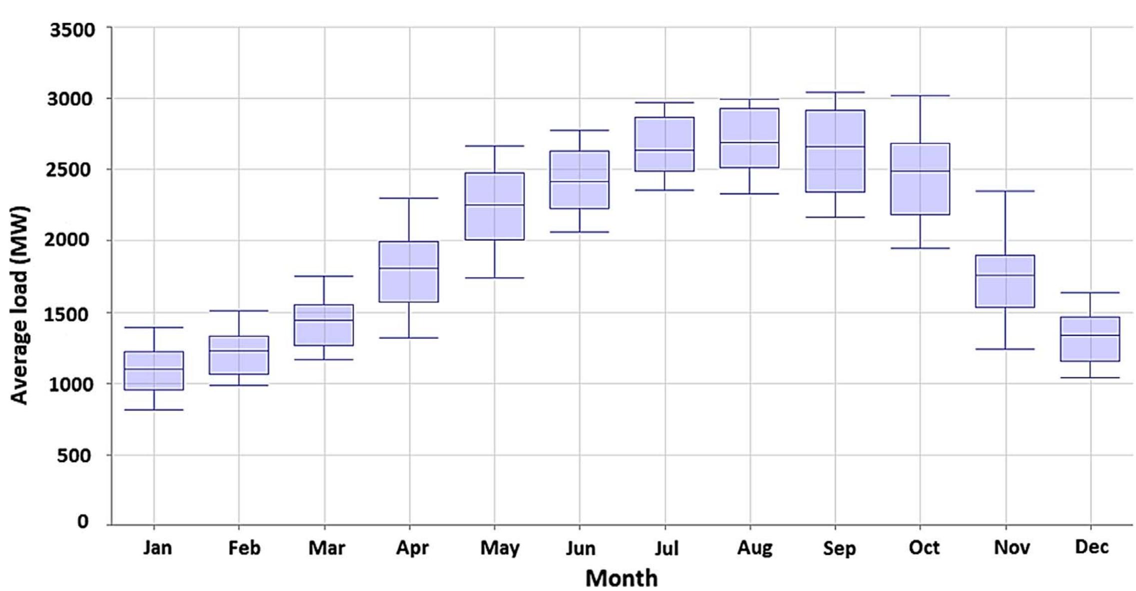

Fig. 11. The monthly average load profile for Makkah.

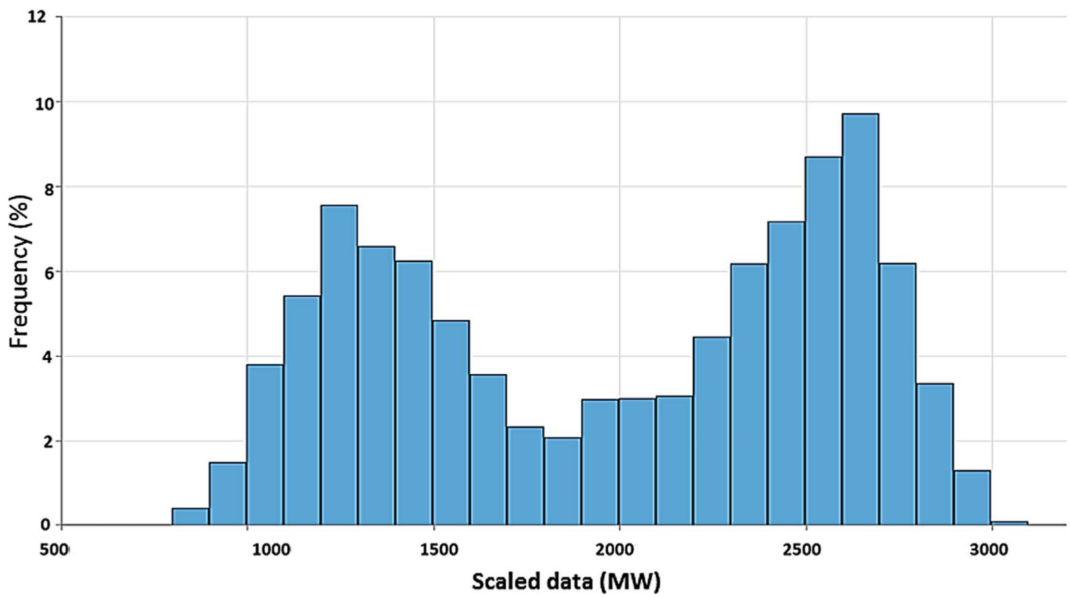

Fig. 12. Histogram graph of the load profile.

Table 1
Consumption rates for residential category in Saudi Arabia [8]

Consumption categories (kWh)	Residential rate (¢/kWh)
1–2000	1
2001–4000	3
4001–6000	5
6001–8000	8
> 8000	

6. **Two-axis (TA):** the panels rotate in both axes (horizontal and vertical) continuously in order to maintain the perpendicular angle between PV panels and sun rays.

A study of each design's impact on the system economic and technical performance is carried out. The cost of the tracking system components excluding the PV module cost are given in Table 3.

For moderate latitude locations (less than 30°), which is the case of Makkah, it is generally accepted that the tilt angle is approximately equal to the latitude which typically maximizes the annual PV energy production [68]. Therefore, the tilt angle for the FT system for the location of Makkah is considered equal to 21.39°. This is identical for VCA where the tilt angle is fixed while the azimuth is changing continuously. The rest of the trackers system have variable tilt angle as part of each tracker scheme.

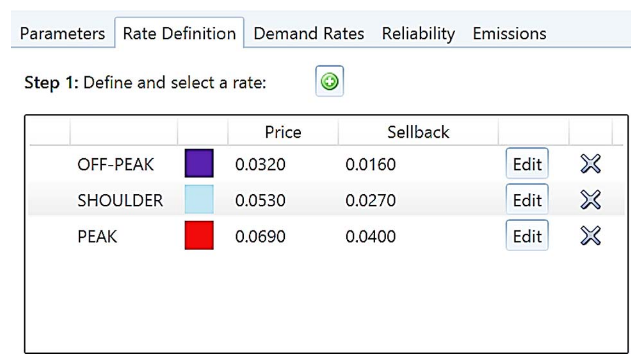

Fig. 14. The scheduled rates for different time during the day [25]

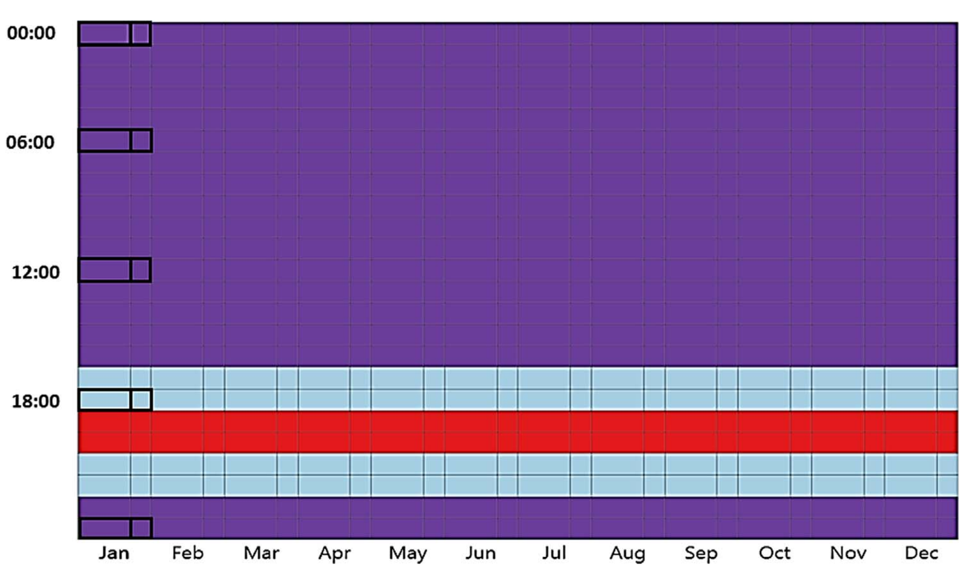

Fig. 13. The grid scheduling rate during the day in each month.

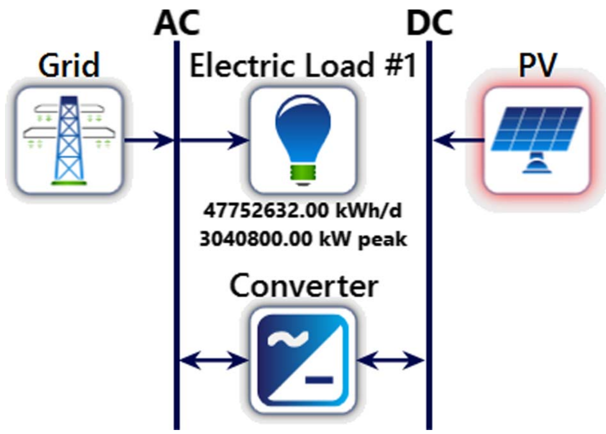

Fig. 15. Design configuration of PV grid-connected system.

5. Results and discussion

The results and discussion of different grid-connected solar PV system designs are presented in this section. Seven cases of tracking systems are examined to determine the most efficient alternative in terms of both technical and economic measures. The performance results and analysis of the panel with no FT, as well as the results of HMA, HWA, HDA, HCA, VCA, and TA are investigated in the next subsections.

5.1. Comparison of various tracking designs on technical performance

For the FT scenario, the annual average electricity production from PV is about 32.11% (5,595,937 MWh/year) of the total generation, while the remainder of the necessary power in this case is purchased from the grid, as shown in Fig. 17. Therefore the major share of the power is obtained from the grid to meet the load requirement and to keep zero unmet energy by the system.

The PV system generates power during the daylight period, with a peak output around noon as illustrated in Fig. 18. The system operates 4404 h throughout the year, with an average output of 1500 MW/day.

In order to investigate the air temperature impact on the power generated by the PV system, the yearly average of a real air temperature for Makkah was used in addition to the temperature coefficient from Table 2 in the PV parameters. Owing to the negative temperature coefficient of solar panels, the power output from the PV system decreases as the temperature increases. As predictable, during the summer season when the average temperature ranges between 30 and 45 °C the system efficiency declines as shown in Fig. 19.

Undoubtedly, the amount of solar irradiation received by panels is a determining factor for their output. Fig. 20 illustrates the average output power generated by different tracking designs on a daily basis. It was found that all the tracking systems produce similar amounts of power at noontime while the power density varies noticeably in the morning and evening hours. Obviously, the TA generates considerably more power in the shoulder periods of the day compared to the other trackers, and it was found to provide 34% more electricity than the FT. The TA has a distinctive feature as it can rotate according to the sun direction on a daily and seasonal basis. Consequently, during the morning and evening hours, TA directs the panels towards the sun and captures more irradiation than the other trackers. On the other hand, FT shows the lowest daily output power whereas the HDA, HWA, HMA generate similar amounts of power. HCA produces 2.4% more power than the other three horizontal trackers. This slight improvement is owing to the continuous adjustment of the panels from morning to evening. The simulation shows a significant amount produced by VCA, 20% more than FT.

The excess electricity production occurs when total production of solar PV surpasses the amount of consumption. The surplus power is normally dumped or curtailed. However, in the proposed system, the excess power will be sold back to the grid at the rates previously described in Fig. 14. Such grid-connected scheme can take advantage of the unused power and gain additional revenues for the system. As shown in Fig. 21, FT yields the lowest excess power (37,923 MW/year), whereas all the horizontal axis tracker designs (HMA, HWA, HDA, and HCA) give similar amounts of excess electricity (around 66,000 MW/year). On the other hand, TA gives the highest amount of excess electricity, almost 400% more than FT. VCA presents a reasonable amount or excess electricity compared to the other trackers.

Through comparative analysis of the six tracking designs in terms of monthly power generation, the variance in the efficiency of various tracking systems is illustrated in Fig. 22. TA design shows the highest power generated from the PV system, with a maximum of 912.4 MW in April and the minimum in December. Furthermore, HMA, HWA, and HDA show very similar production. However, from May to June, HDA and HWA were able to generate 2.5% (17.8 MW) more power than HMA as shown in Fig. 23. FT demonstrated the lowest performance during summer period, as a result of the movement of sun's orbit to the north in addition to the high-temperature impact. This highlights the significance of adjusting the tilt angle regularly.

The percentage difference in electricity generation by different tracking systems in comparison to the FT is shown in Table 4. It can be noted that TA generates the highest power output, with an hourly average of 861.3 MW which exceeds the FT system production by 34.84%. It should also be noted that PV panels mounted with horizontal-axis (HCA, HDA, HWA, and HMA) show relatively small differences in capacity, with a slight improvement compared to FT system (5–8%). Power generated with VCA trackers was 20% more than power generated with FT due to increased production during daily tracking.

As the output power generated by a PV system increases, the power purchased from the grid declines instantaneously. As shown in Fig. 24, the sum of the PV power and the grid power is equivalent to the total electrical load served, which means that the system has delivered the right amount of power with zero unmet power demand.

5.2. Comparison of various tracking designs on system economics

By applying Eqs. (1) and (2), HOMER calculates NPC and LCOE for the entire system. Fig. 25 shows the cost summary of FT scheme by components. The power purchased from the grid, which is considered an operation cost, represents the highest cost. It amounts to \$6361 million with a constraint of no unmet power. The total NPC of the system is \$10,233 million whereas the LCOE is \$0.0441/kWh. Since

Table 2
PV and converter parameters.

Component	Size	Lifetime (years)	Cost			Other information	Reference
			Capital (\$)	O & M (\$/year)	Replacement (\$)		
PV	1 kW	25	640	10	640	• α_P = -0.40%/°C • f_{PV} = 90% • Efficiency = 18%	[65]
Converter	1 kW	25	375	10	\$375	• Efficiency = 97%	[66]

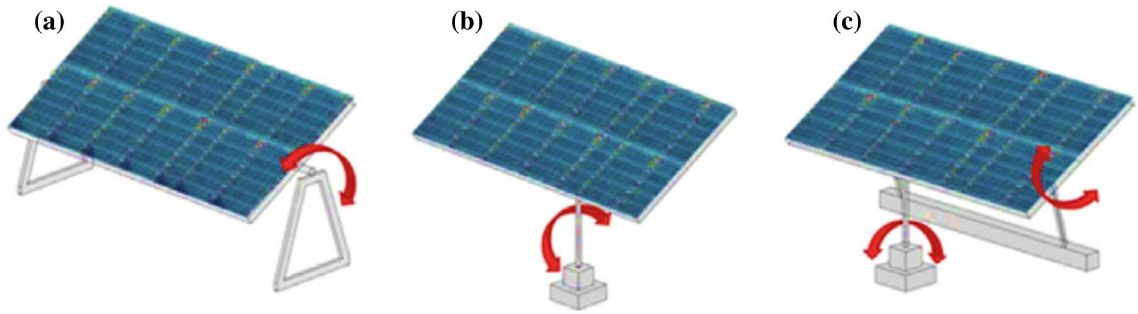

Fig. 16. Illustrations of (a) horizontal axis, (b) vertical axis and (c) two-axis tracking system [67]

Table 3
Cost inputs for the different tracking systems [67]

No.	Tracking system	Capital cost ($/kWh)
1	Horizontal-axis, daily, weekly, and monthly tracking system	563.00
2	Horizontal-axis, continuous adjustment	870.00
3	Vertical-axis, continuous adjustment	255.00
4	Two-axis	1000.00

there is no tracking, the PV component cost of $2339 million has a moderate cost compared to other tracking systems scenarios.

It is interesting to discuss the purchasing and selling periods throughout the year. The power flow during the year to and from the grid for the tracking scenario FT is depicted in Fig. 26, where three periods can be distinguished. In the first three months of the year (period 1), the air temperature and the customer load are lowest. Consequently, the system shows the highest amount of power sold to the grid, reaching 1000 MW. However, during most of the year (period 2) the system becomes more reliant on the grid due to high demand in addition to the rising temperatures (over 40 °C). Finally, in period 3, the system resumes generating more power than required by the load and selling the surplus to the grid. Power purchasing from the grid is continuous throughout the year, with a maximum of 2931 MW during August and September.

The findings of the different tracking simulations show that FT has the lowest NPC and LCOE as shown in Fig. 27. This is due to the relatively low power generation cost along with the low cost of the simple system. Conversely, HCA demonstrated the highest NPC and LCOE of $12,662 million and 0.05434 $/kWh respectively. Despite the daily and weekly adjustment of the tilt angle in HWA and HDA, results presented almost the same as each other in terms of LCOE and NPC values. Moreover, there are no significant differences between HMA, HWA, and HDA regarding LCOE, whereas HCA had the highest LCOE followed by TA. On the other hand, the VCA tracking system showed enhanced performance. Consequently, in this scheme less power is purchased from the grid, which reduces its NPC (10,470 million) and LCOE (0.04475 $/kWh). In spite of the high contribution of renewable energy to the system by HCA and TA, the high costs of grid purchases and the tracking system components boost the LCOE for these two systems compared to other trackers.

Due to the differences in cost of solar tracking systems and in solar irradiation, the optimal solar tracking design may vary for different locations. The results obtained using HOMER software in this research could be compared with the results from existing projects with similar solar irradiation. In the United States, more than 50% of the utility-scale operating solar PV (which account for 60% of the total solar PV unit capacity) use either single-axis or dual-axis form of tracking system [69]. These tracking technologies tend to be located in the Southwest where the solar irradiation ranges from 5 to 6 kWh/m^2/day, which is comparable to that in Makkah, Saudi Arabia.

In comparison to the reference case which is the FT, all the horizontal axis trackers demonstrate a negative ROI (−3.3%) as shown in Fig. 28. This is mainly due to the high capital cost at the year zero of the project. On the other hand, despite the double capital cost of the TA system compared to the reference, the negative impact on the TA's ROI is mitigated by a higher efficiency throughout the project lifetime which is considered as 25 years for all designs. The ROI of the TA is −1.8%. Notably, TA can generate extra power and sell it to the grid. Ultimately, VCA shows a positive ROI (+1.73%) which makes it the best option since it generates a profit in the project lifetime. We should also bear in mind that solar tracker prices are anticipated to continue falling in the coming years, as the historic drivers including the steadily reducing production costs and the market expansion are likely to continue into the future. Therefore, the ROI of all trackers will increase.

6. Conclusion and future works

The following are the key findings and contributions of this research:

- Grid-connected solar PV systems with different tracking system designs, including different time adjustments of the tilt angle, have been examined and compared. An optimal design of a utility size solar-PV grid-connected system for a specific location has been demonstrated. Six tracking designs including FT, HMA, HWA, HDA, HCA, VCA, and TA are considered as viable options for a solar PV grid-connected system. The techno-economic performance of the

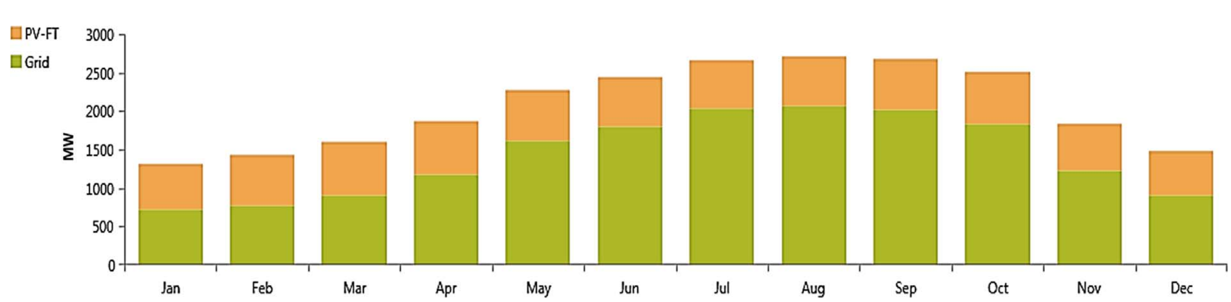

Fig. 17. The monthly average electric production.

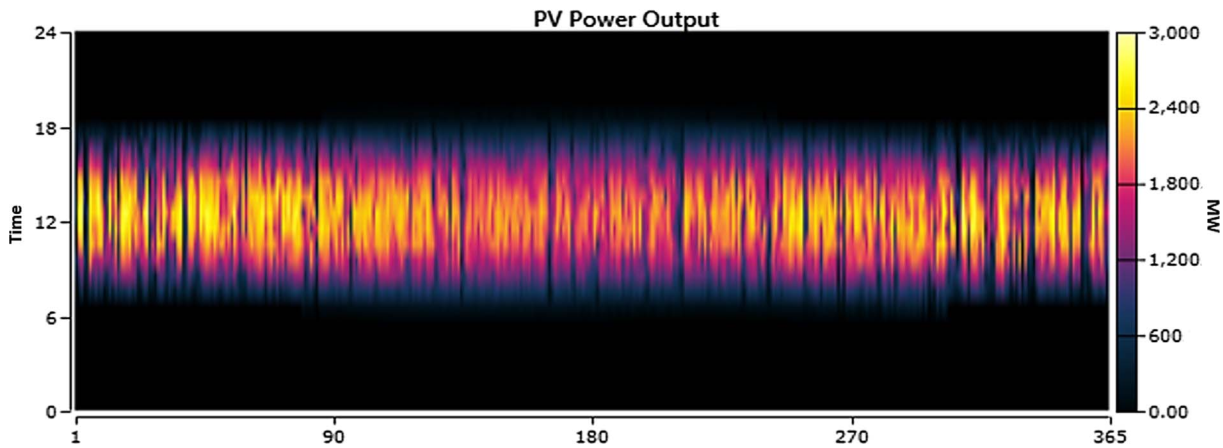

Fig. 18. PV power output throughout the year and daytime.

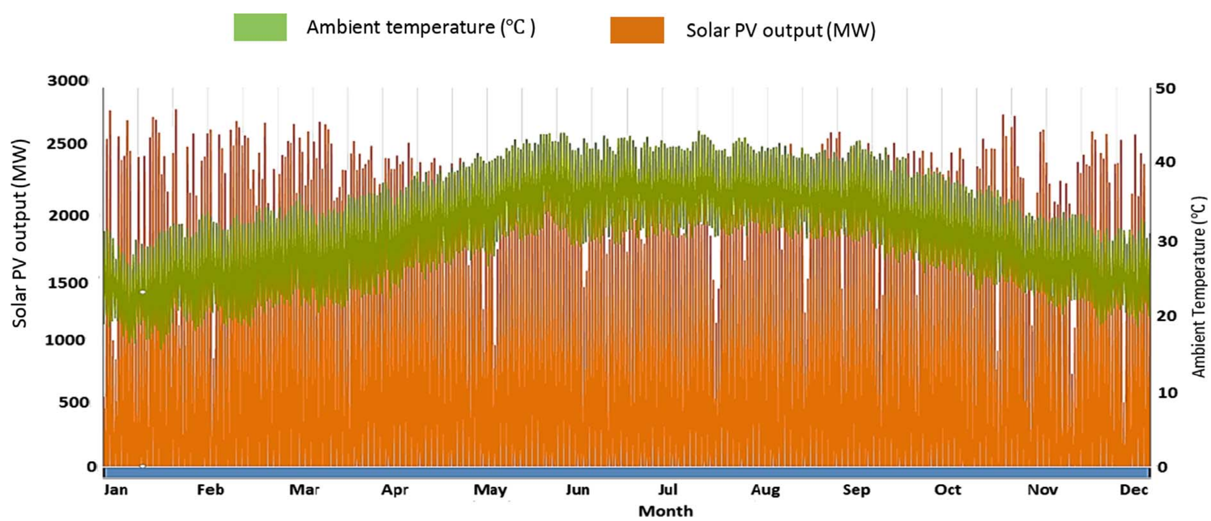

Fig. 19. Solar PV production versus ambient temperature throughout the year.

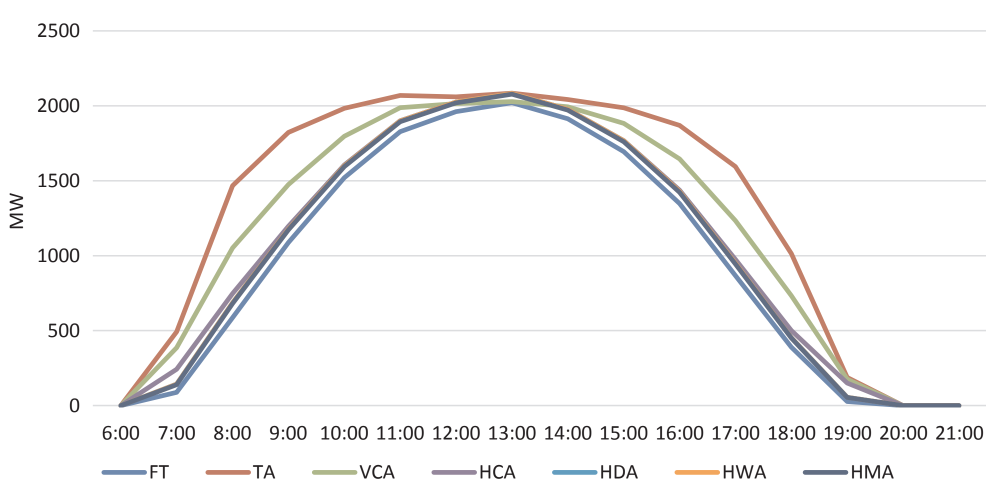

Fig. 20. Average daily power graph of the different tracking systems.

different tracking schemes was assessed using HOMER simulation tool and discussed.

- In a comparative analysis of daily power generation, all the tracking systems produce similar power output at noontime while the power density varies noticeably in other periods. The results reveal that TA can produce 34% more power than FT, which was the base case and the lowest producing scheme, while VCA can produce up to 20% more power than FT. The different time adjustments of the tilt angle in HAD, HWA and HMA designs had no significant effect on the amount of power generated compared to each other. Whereas HCA produced only 2.4% more than HDA.
- Regarding excess power, TA similarly produced the highest amount, 400% more than FT. All horizontal axes trackers (HMA, HWA, HDA, and HCA) produced similar amounts of excess electricity as each other. VCA produced a reasonable amount compared to other trackers.

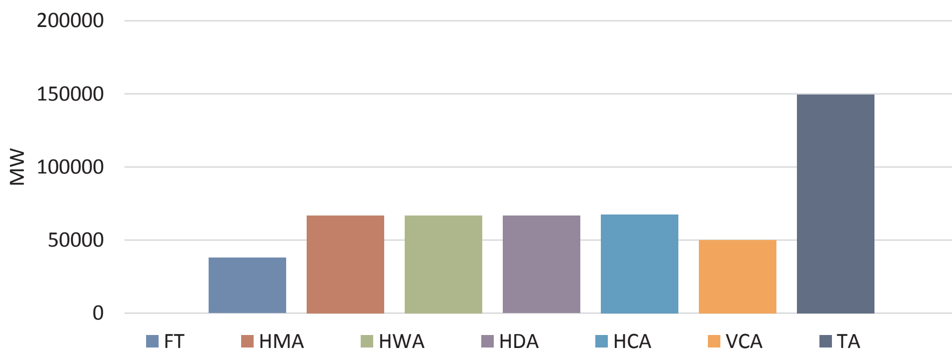

Fig. 21. The excess electricity of different trackers per year.

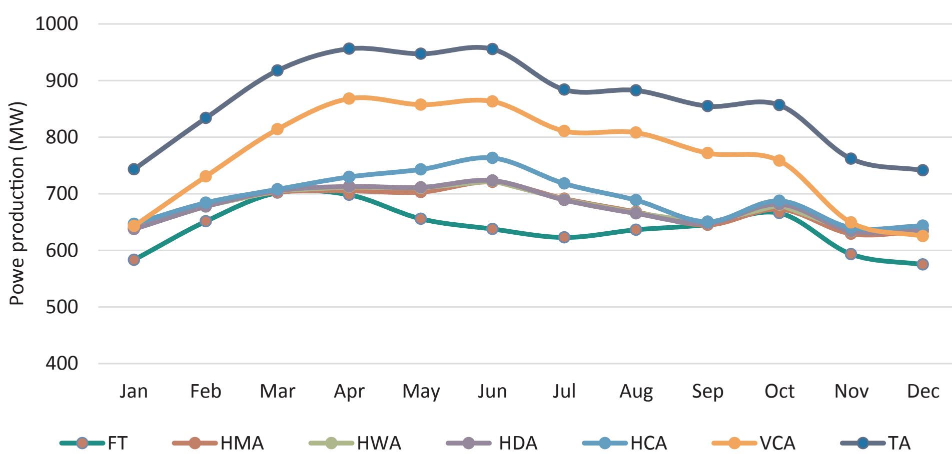

Fig. 22. Monthly power generation from various tracking systems.

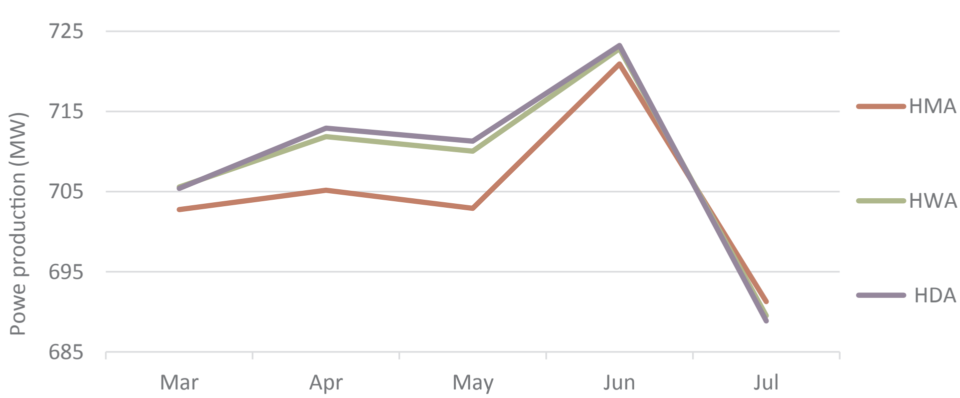

Fig. 23. Horizontal trackers performance from March to July.

Table 4
Hourly power production along with comparison to non-tracking system.

Tracking system	FT	TA	VCA	HCA	HDA	HWA	HMA
Hourly average power (MW)	638.8	861.3	766.8	691.9	676.7	676.6	674.2
PV power output Vs FT (%)	0	34.84	20.04	8.32	5.94	5.92	5.54

- The study findings show that FT design has the lowest NPC and LCOE, $10,233 million and 0.04907 $/kWh respectively. This is mainly due to the relatively low power generation cost along with the low cost of a simple system. Moreover, there are no substantial differences between HMA, HWA, and HDA regarding LCOE whereas HCA had the highest costs, followed by TA. VCA is able to sell back excess power produced mainly in low temperature and low demand periods (January – May). It showed less power purchased from the grid than FT and other one-axis trackers which lead to lower the NPC and LCOE.
- In comparison to the fixed system, the tracking systems require higher initial, operation, and maintenance costs. Vertical continuous tracking system presents a high penetration of solar energy to the grid, and it has relatively low LCOE and NPC. Moreover, it introduced the only positive ROI compared to all trackers.
- Considering the high cost of the two-axis tracking system and the low performance of horizontal trackers, the VCA offers a significant technical performance along with feasible economic metrics (LCOE, ROI and NPC). Therefore, VCA can be recommended as the optimal choice for Makkah city, to enhance the electricity generation of grid-connected solar PV.
- The proposed system design and evaluation of tracking systems could be applied to any location worldwide to improve the performance of grid-connected solar PV. However, the simulation results in this study are quite dependent on site metrological conditions, the load profile, and the components cost which may vary by location.
- HOMER software is a powerful tool to evaluate designs of a variety

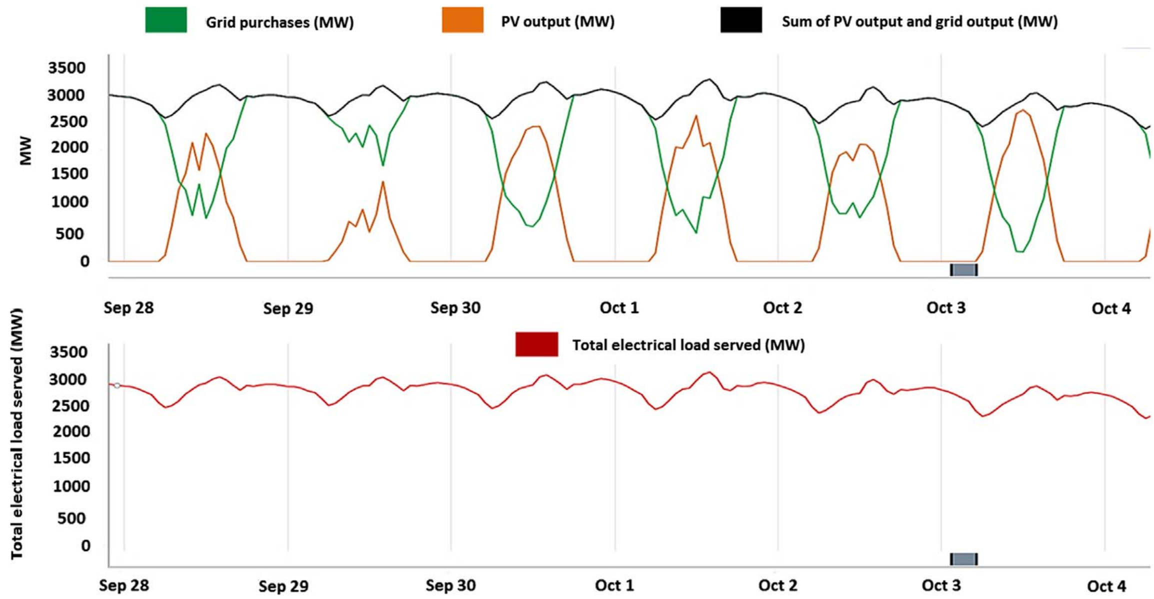

Fig. 24. The production of PV system along with grid to maintain load demand.

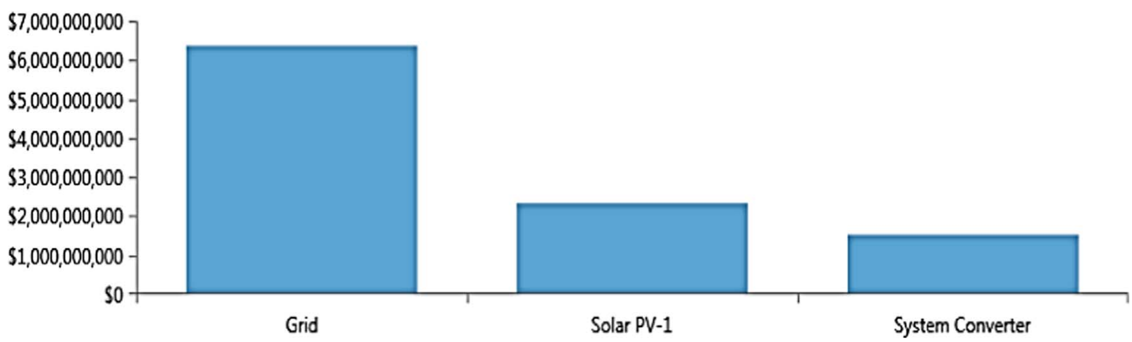

Fig. 25. Simulation results of net present cost of FT system.

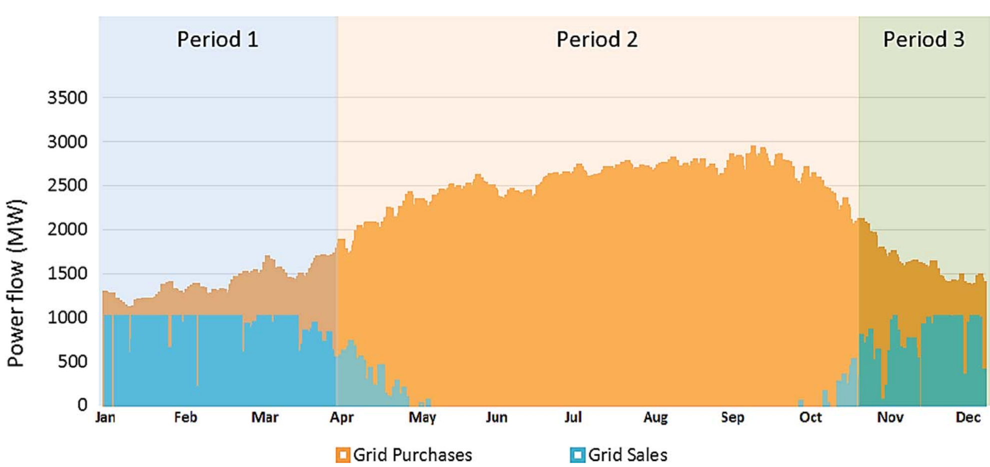

Fig. 26. Energy purchased from grid and energy sold to grid.

of tracking configurations for grid-connected applications, as it considers the key factors of PV system performance including load profile, component costs, and resource availability.

To conclude, this study further enriches the body of knowledge about the feasibility, technical performance, and economic aspects of grid-connected solar PV with different tracking systems and different time adjustments. Nevertheless, several possible limitations need to be considered. First, REFIT can play a vital role in the RES economic viability, and further analysis could be carried out to observe its impact on the economic performance of the system. Moreover, the effect of different models of solar PV with different temperature coefficients and their effect on power generation, NPC, and LCOE could be investigated. In the future research, a comparative performance analysis of off-grid and grid-connected designs for various locations with different metrological conditions will be investigated. Moreover, hybrid systems such as solar-wind-biomass could be integrated to examine the optimal design.

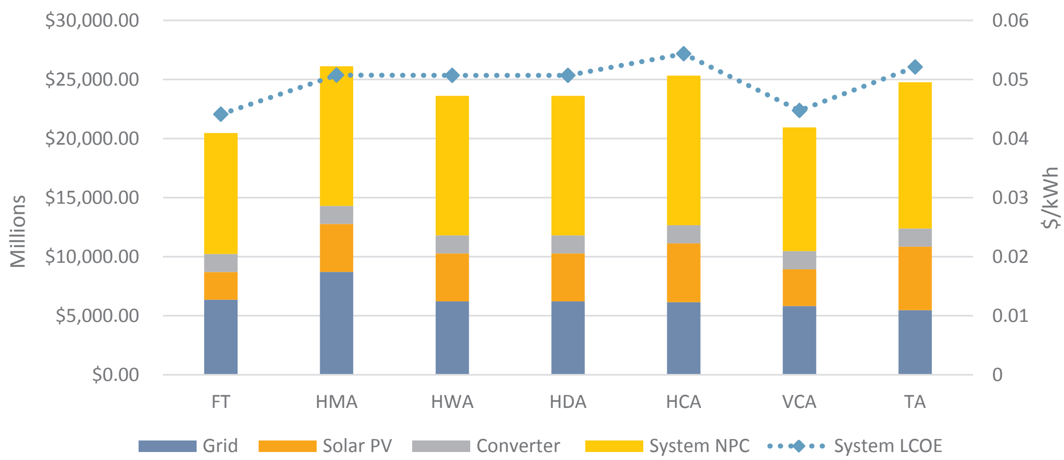

Fig. 27. NPC and LCOE for various scenarios of tracking systems.

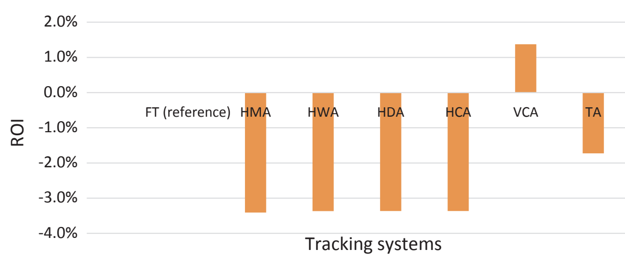

Fig. 28. Return on investment with FT as the reference case.

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