Renewable Energy 75 (2015) 489–495

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Optimal sizing of grid-connected photovoltaic energy system in Saudi Arabia

Makbul A.M. Ramli [a], [*], Ayong Hiendro [b], Khaled Sedraoui [a], Ssennoga Twaha [c]

[a] Department of Electrical and Computer Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia
[b] Department of Electrical Engineering, Universitas Tanjungpura, Pontianak 78124, Indonesia
[c] Department of Sustainable and Renewable Energy Research, Skyline Technical Services Ltd., P.O. BOX 27853, Kampala, Uganda

ARTICLE INFO

Article history:
Received 7 April 2014
Accepted 11 October 2014
Available online

Keywords:
Grid-connected photovoltaic system
Carbon dioxide emissions
Excess electricity
HOMER
Optimization

ABSTRACT

Resource optimization is a major factor in the assessment of the effectiveness of renewable energy systems. Various methods have been utilized by different researchers in planning and sizing the grid-connected PV systems. This paper analyzes the optimal photovoltaic (PV) array and inverter sizes for a grid-connected PV system. Unmet load, excess electricity, fraction of renewable electricity, net present cost (NPC) and carbon dioxide (CO_2) emissions percentage are considered in order to obtain optimal sizing of the grid-connected PV system. An optimum result, with unmet load and excess electricity of 0%, for serving electricity in Makkah, Saudi Arabia is achieved with the PV inverter size ratio of $R = 1$ with minimized CO_2 emissions. However, inverter size can be downsized to 68% of the PV nominal power to reduce the inverter cost, and hence decrease the total NPC of the system.

1. Introduction

In Saudi Arabia, almost all electricity is generated using diesel except some generated from renewable energy. The price of diesel in this country is about USD 0.096 per liter, which is one of the cheapest in the world. It makes diesel power generation less expensive than photovoltaic (PV) systems, although the Kingdom has high solar radiation of up to 2200 kWh/m^2/yr and the prices of PV panels are decreasing on the world scale.

The use of renewable energy, which is part of Saudi Arabia's energy conservation policy, provides great benefits to the Kingdom. With abundant solar resources, the Kingdom has an option to reduce domestic diesel consumption and increase its oil exports, a practice which ought to come with social and economic benefits of reduced CO_2 pollution and increased revenue from oil respectively. Since renewable energy use offers environmental benefits in form of reduced CO_2 pollution, combining several renewable energy sources to form hybrid systems, whether off-grid or grid-connected systems as suggested in Refs. [1–6] can provide more benefits by reducing CO_2 emissions and providing a reliable supply of electricity in all load conditions. However, this cannot be achieved if only diesel power generation systems are utilized. CO_2 capture and storage (CCS) technology can also be considered to mitigate CO_2 emissions from power generation systems [7], though this type of technology is not yet expected to be realized in the near future [8]. Mahmoud and Ibrik in Ref. [9] have studied a PV system applied to Palestine with the conclusion that the PV system is more economic and environmentally friendly than either diesel power generation or electric grid systems.

In many countries, serious efforts have been made to supplement conventional power generation with the grid-connected PV systems. The systems do not only offer electric utility and environmental benefits, but also customer benefits [10]. Customer benefits are obtained by selling excess PV electricity to the grid. This can be done by customers who are located close to the grid [11]. Eltawil and Zhao [12] have shown that the growth-rate trend for grid-connected electricity is increasing annually and has become the dominant market for PV-generated electricity.

Optimizing the PV array and inverter sizing are necessary design aspects for grid-connected PV systems. In Ref. [13], Mellit et al. have reviewed various techniques for sizing PV systems, i.e. stand-alone, hybrid off-grid and grid-connected systems. They concluded that when the all required data is available, the conventional sizing methods (empirical, analytical, and numerical) present good solutions.

In the design and installation of grid-connected PV systems, the inverter ratings are recommended to be smaller than those of PV arrays [14–18]. One of the reasons for this recommendation is because it is usually rare for the PV arrays to produce DC output

---

[*] Corresponding author. Tel.: +966 2 6402000.
E-mail address: mramli@kau.edu.sa (M.A.M. Ramli).

http://dx.doi.org/10.1016/j.renene.2014.10.028
0960-1481/

power equivalent to, but in most cases less than their ratings. However, Chen et al. [19] have shown that the optimum inverter size can either be lower than or the same as the PV array rated size, basically due to meteorological factors, economic factors and inverter intrinsic parameters.

In some cases, grid-connected PV systems do not usually have battery storage. In such scenarios, excess energy after supplying the primary load from the PV array can be sent to the utility grid. On the other hand, energy can be drawn from the grid when energy generated from PV is insufficient for the primary load. Therefore, the difference between price of buying electricity from the grid and that of selling to the grid from the PV system is a substantial factor in determining the optimal size of grid-connected PV systems [20–22].

Real-time electricity pricing of PV generation systems integrated to the utility grid is possible by using appropriate distributed control frameworks such as the supervisory predictive controllers to operate the integrated systems to achieve short and long term optimal management and operation control [23]. Moreover, the supervisory predictive control methods applied to hybrid solar/wind systems ensure high computational efficiency of the control problem, thereby guaranteeing their effective applicability to the supervisory control system designs [24]. The supervisory predictive control method [24,25] can also be implemented to schedule operation and maintenance (O&M) time of inverters and PVs and have been proved to be part of the framework for the smart grid.

In other research works [26,27], various PV module technologies have been studied. Notton et al. in Ref. [28] have concluded that the PV module technology does not significantly influence the optimum size of grid-connected PV systems.

The main objective of this paper is to investigate the optimal PV, inverter and PV/inverter sizes for a grid-connected PV system in Makkah, Saudi Arabia. Net present cost, renewable electricity fraction, excess electricity, and CO_2 emissions are factors that are being analyzed using HOMER simulation [29].

2. HOMER software

The Hybrid Optimization Model for Electric Renewables (HOMER) software tool, developed by the National Renewable Energy Laboratory (NREL) is being utilized in the current study [29,30]. The HOMER simulation software performs the analysis of the grid-connected PV systems by simulating the system operation and cost evaluation for the project's lifetime. This simulation requires data on initial capital, O&M, as well as replacement costs. Several researches have been conducted using this software for optimal design, planning, and sizing of renewable energy resources such as solar, wind, hydro etc. for both off-grid and grid-connected systems as well as their capability in reducing dependence on fossil based electricity generation [31–33].

Table 1
Primary load baseline.

	Baseline	Scaled
Average (kWh/day)	32,962,422	32,962,332
Average (kW)	1,373,434	1,373,431
Peak (kW)	2,213,000	2,212,999
Load factor	0.621	0.621

3. Input parameters used for the simulation

3.1. Load profile

The electricity demand in Makkah varies monthly dependent on various factors. The reasons for the variations in the electricity consumption in Makkah are due to: 1) Special occasions (Eid al-Fitr, Kingdom National Day); 2) Religious occasions (Hajj, Ramadan, Umrah); and 3) Climatic changes. The maximum peak load consumption occurs in the summer season. Sometimes there is an overlap between the summer months and the Hajj or Ramadan month resulting in high energy consumption in that period of time. The monthly load profile of Makkah is presented in Fig. 1. From the load profile, it is shown that the peak load in Makkah is about 2200 MW with energy consumption of 33,000 MWh/day observed in the month of November in Fig. 1. The primary load baseline generated by HOMER is presented in Table 1.

3.2. Solar radiation

In HOMER, the solar resource input can be represented by either the solar radiation data or the clearness index. Based on data accessed from Ref. [34], the solar radiation in Makkah (latitude = 21°26′ North and longitude = 39°49′ East) is between 4.15 kWh/(m^2 day) and 7.17 kWh/(m^2 day). The average solar radiation over the year is 5.94 kWh/(m^2 day). Solar irradiance is high (above the average) from March to September, with a peak in the month of June, while solar irradiance is low in January, February, October, November and December. Fig. 2 shows the solar radiation data used in the simulations. The left side axis represents the solar radiation while the right one represents the clearness index.

3.3. Energy price

Mondol et al. in Ref. [21] limit the excess PV electricity fed to the grid when the electricity buying price is higher than the selling price. However, this limit increases the surplus electricity that in turn must be dumped because it can neither be used to serve a load nor charge the batteries. In this study, all excess electricity from PV is sold to the grid to suppress unused electricity. The selling price is always made higher than the buying price as shown in Fig. 3, so that the profitability can be realized by selling the electricity to the grid. The selling and buying prices of excess electricity from PV is a part

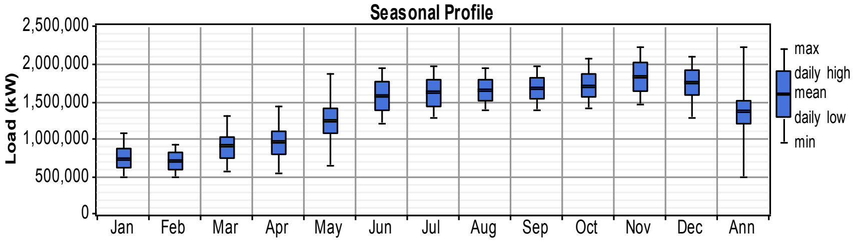


Fig. 1. Monthly load profile of Makkah.

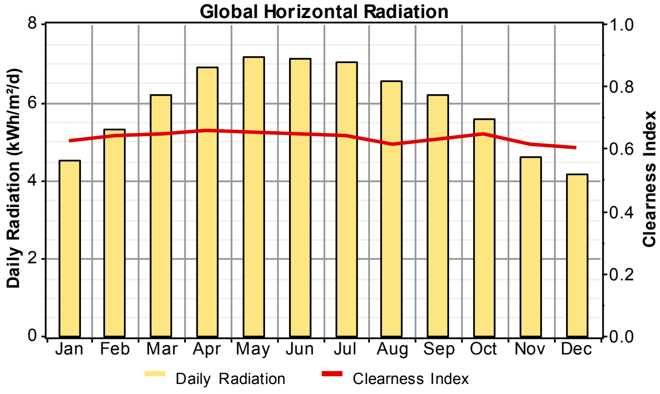


Fig. 2. Solar radiation data.

of the energy conservation policy. With this policy, the Kingdom of Saudi Arabia encourages and supports the reduction of domestic diesel consumption and therefore subsidies can be offered to reduce the selling price of electricity from PV to consumers.

The buying prices for renewable energy are assumed to be \$0.016/kWh during off peak hours, \$0.027/kWh during shoulder hours, and \$0.040/kWh during peak hours. The period schedules (off-peak, shoulder and peak hours) are not changed in the simulation for simplicity of the analysis.

4. Design specification

In this design, the system consists of a PV panel, inverter, grid and the load as shown in Fig. 4. When the battery back-up capacity is excluded, the cost of the whole system decreases by around 40–50% depending on the type of batteries used and the capacity required. Therefore, since the system is connected to the grid, a condition that improves the reliability of supply to the load, the battery storage has been excluded from the system for economic benefits of reduced system cost.

4.1. PV arrays

The size of PV arrays is dependent on the solar radiation available, the load profile and the renewable fraction required. The energy derived from renewable resources and used as part of supply to the load is defined as the renewable fraction, and in this case the renewable fraction is related to the PV production. The PV size can either be increased or decreased, according to the amount of unmet electric load and renewable fraction set in the design. PV size adjustment ensures that the variation in load demand in a year is well catered for. In the present study, generation of power is done by PV only from 6 a.m. to 6 p.m. The PV cost data is provided in Table 2.

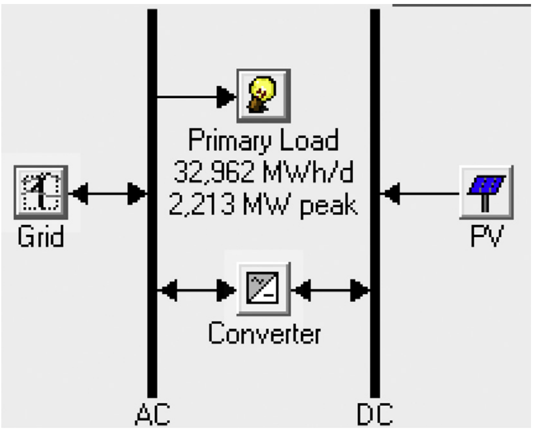


Fig. 4. Grid connected PV system.

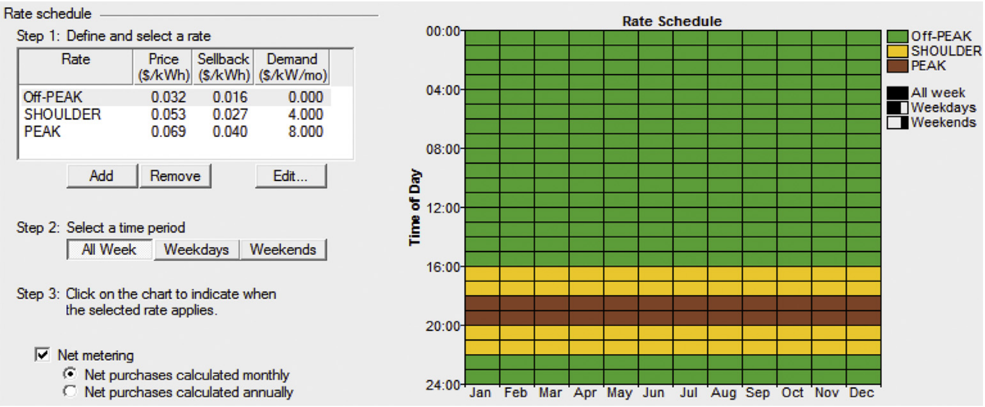
PV lifetime is set at 20 years. PV panels typically have their best performance within 20 years and subsequently their output continuously degrades after 20 years.

The average price of a PV panel, including the installation cost, was set at \$ 2500/kW in the simulation. During operation, normal maintenance is required, though there is no operation cost. Compared to the capital and installation cost, the operation and maintenance (O&M) cost is fairly small. For each kW of PV array, the O&M cost was estimated to be \$ 10/year. The O&M cost includes the cost to remove dirt and dust on the PV panel and the PV panel direction adjustment.

4.2. Inverter

The PV arrays produce direct current (DC) at a voltage, which depends on the specific design and the solar radiation. The DC power then runs to an inverter, which converts it into standard AC voltage. Inverters commonly used in large scale applications are central inverters that offer easy installation and high efficiency. The average price of PV inverter (central inverter) used in this project is set at \$400/kW. Inverter O&M cost is estimated to be 5% of the total investment per year.

The inverter size depends on maximum DC input power (i.e. size of the PV array in peak watt) as well as the maximum specified output power (i.e. the AC power provided to the grid). The



Rate schedule

Step 1: Define and select a rate

Rate	Price ($/kWh)	Sellback ($/kWh)	Demand ($/kW/mo)
Off-PEAK	0.032	0.016	0.000
SHOULDER	0.053	0.027	4.000
PEAK	0.069	0.040	8.000

Step 2: Select a time period

Step 3: Click on the chart to indicate when the selected rate applies.

☑ Net metering

● Net purchases calculated monthly

○ Net purchases calculated annually

Fig. 3. Electricity buying and selling prices.

Table 2
PV data.

PV panel	
Lifetime	20 yr
Derating factor	90%
Capital cost per kW	$ 2500
Replacement cost per kW	$ 2000
O & M cost per kW per year	$ 10

Table 3
Inverter data.

Inverter	
Lifetime	10 yr
Efficiency	90%
Capital cost per kW	$ 400
Replacement cost per kW	$ 375
O & M cost per kW per year	$ 20

appropriate inverter size is able to maximize the quantity of energy harvested from the PV arrays in addition to minimizing inverter cost. However, the overall system performance will not be affected or reduced.

The inverter data is summarized in Table 3.

4.3. Grid

When the PV system is connected to the grid and interconnected with other power generating devices, the grid capital cost is equal to the interconnection charge. Otherwise, the grid capital cost is maintained at zero. In HOMER, the replacement cost of the grid is always zero. The grid O&M cost is equal to the annual cost of buying electricity from the grid (i.e. cost of energy plus demand cost) minus any income from the electricity sold to the grid. The grid O&M cost for the grid-connected PV systems also includes the standby charge.

5. Simulation results

5.1. Optimal sizing of PV

In the simulation, the system performance is set at an unmet load of 0%. However, excess electricity may occur when there is a surplus of generated power after serving the primary load. The excess electricity could have been dumped because it is not used by the load. However, as indicated earlier, in this analysis the excess electricity is sold to the grid at the rates already indicated above. Fig. 5 presents the percentage of excess electricity with PV size variations. There is no excess electricity for the PV size from zero up to 2200 MW.

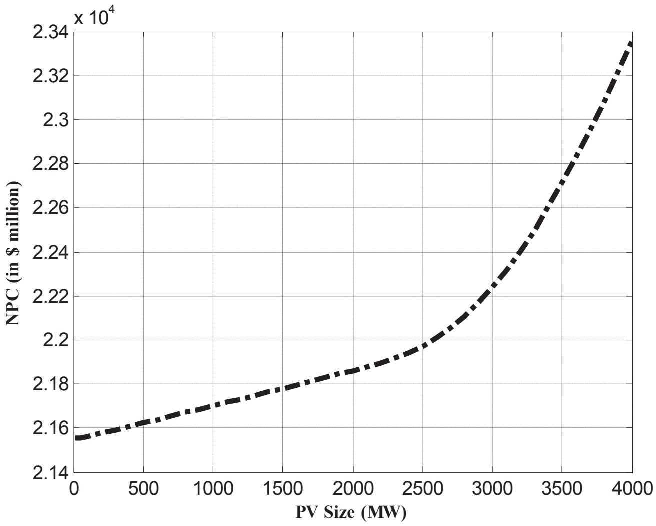


Fig. 6. The total net present cost vs. PV size.

The NPC of the system can be seen in Fig. 6. The system NPC increases with increasing PV size though it is observed to increase significantly when the PV size is higher than 2200 MW.

Electricity supply comes from PV arrays and grid purchases. The percentages of electricity produced by PV and the grid supply are shown in Fig. 7. There is an inverse relationship between the electricity produced from the PV and that supplied by the grid; electricity supplied from PV and the grid increases and decreases respectively with increasing PV size. The intersection point is at a PV size of 3900 MW where the PV arrays and the grid each provide 50% of the total electricity production. For PV size of 2200 MW, 33% of electricity is produced by PV arrays while the grid supplies the remaining 67% of the total electricity production.

Utilizing a bigger size of PV that is connected to the grid will reduce CO_2 emissions as shown in Fig. 8. This is the reason behind using relatively expensive solar PV system when compared to the cheap fossil generated electricity. Therefore, the bigger the PV size,

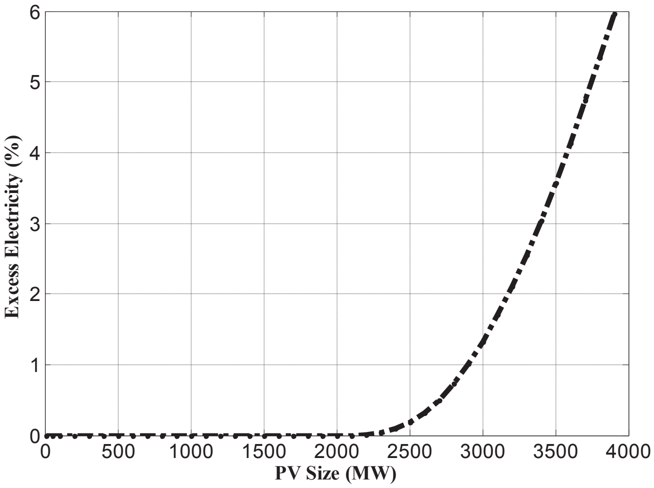


Fig. 5. Excess electricity vs. PV size.

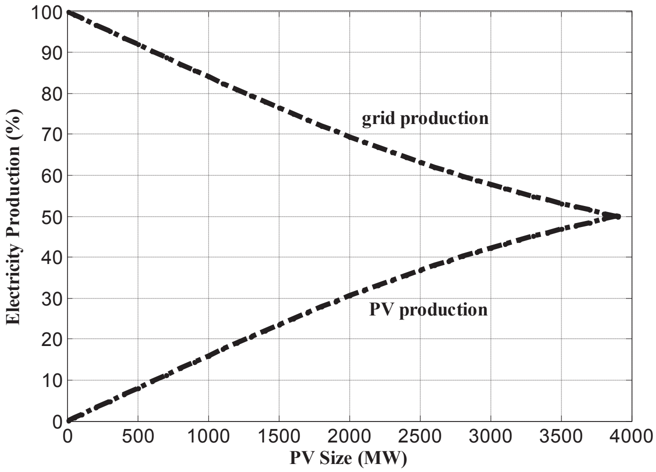


Fig. 7. Electricity production vs. PV size.

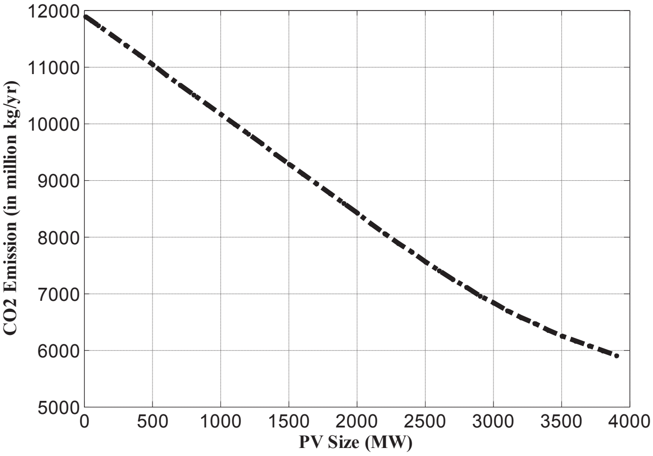


Fig. 8. CO_2 emissions vs. PV size.

the higher the renewable energy fraction and the lower the CO_2 emissions. For grid emission factor of 990 g/kWh, the CO_2 emission is 8,066,000 tonnes/yr for the PV size of 2200 MW.

5.2. Optimal sizing of inverter

Fig. 9 presents the excess electricity vs. inverter size variations for a fixed PV size of 2200 MW. An inverse relationship between the excess electricity and the inverter size can be observed in Fig. 9 with zero excess electricity for the inverter size above 2200 MW. Low inverter sizes reduce the energy harvested from the PV arrays and increase the grid purchases. Hence, this condition results in high excess electricity.

The approximately parabolic relationship between the NPC and the inverter size of the system is shown in Fig. 10. It is clearly shown that the total NPC of the system decreases for increasing inverter size up to 1500 MW, a point at which the minimum NPC is achieved. This is due to the fact that more energy can be sold to the grid if the inverter has more capacity to harvest energy from the PV arrays. However, the NPC increases significantly when the inverter size is higher than 1500 MW. Total electricity production required to meet the load at 1500 MW inverter size (at the minimum value of NPC) is 13,000,000 MWh/yr. This amount of electricity is produced by both PV arrays and grid purchases as presented in Fig. 11. In the situation where a 1500 MW inverter is used in combination with a 2200 MW PV array, unmet load is not found from the simulation and the excess electricity of 1.65% is produced. There is no excess electricity produced for the inverter size of more than 1500 MW and the cost of the inverter will only increase the NPC resulting into the rising portion of the NPC against inverter size curve. Therefore, the inverter size should be kept at an optimum point.

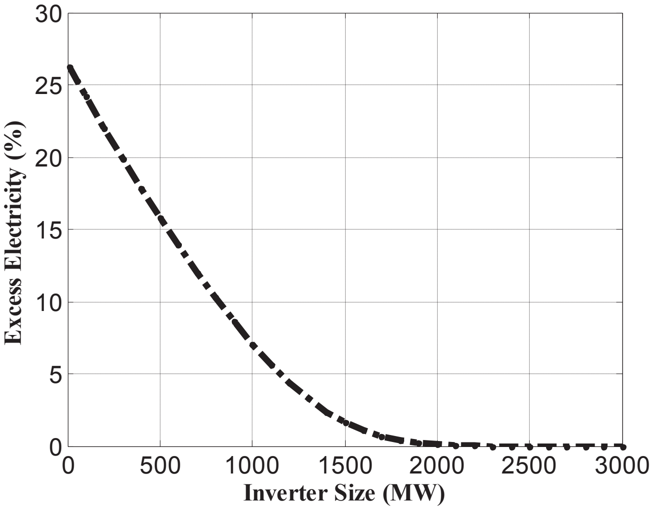


Fig. 9. Excess electricity vs. inverter size.

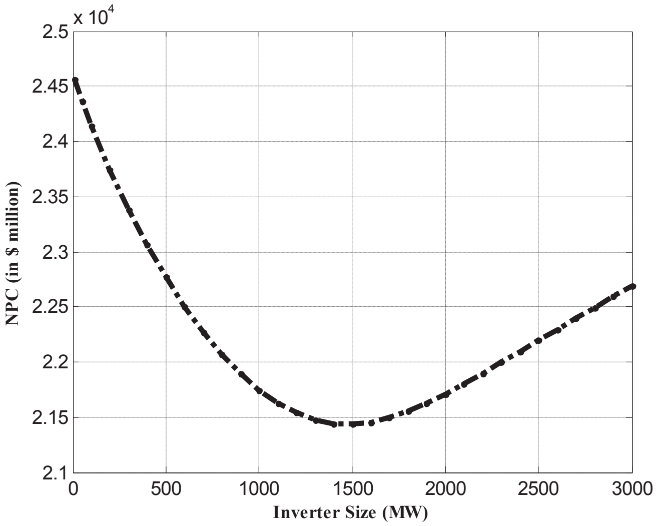


Fig. 10. The total net present cost vs. inverter size.

Utilizing a bigger inverter size can reduce CO_2 emissions, as shown in Fig. 12. However, there is no increase in CO_2 emissions for an inverter size of more than 2200 MW. This is because increasing inverter size beyond PV size of 2200 MW neither affects the power harvested from PV nor the electricity purchase from the grid as shown in Fig. 11 but only increases the NPC as observed in Fig. 10 above, a situation that will keep the CO_2 emission production constant.

5.3. Economic analysis

Based on the results above, two different configurations are taken into consideration for the grid-connected PV system in Makkah, i.e. $R = 1.47$ and $R = 1.00$. R is the ratio between the

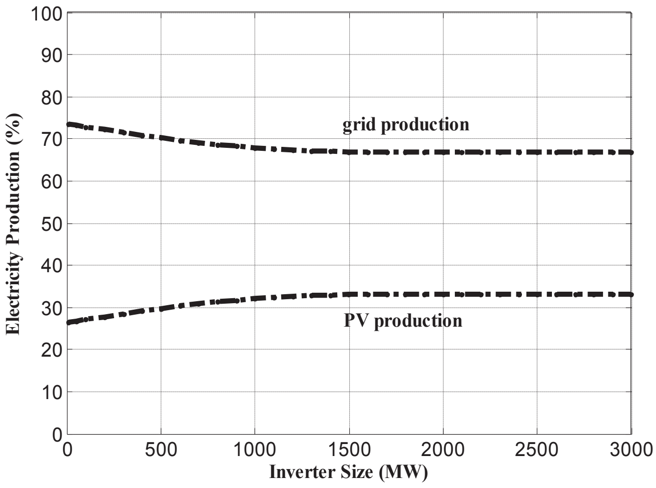


Fig. 11. Electricity production vs. inverter size.

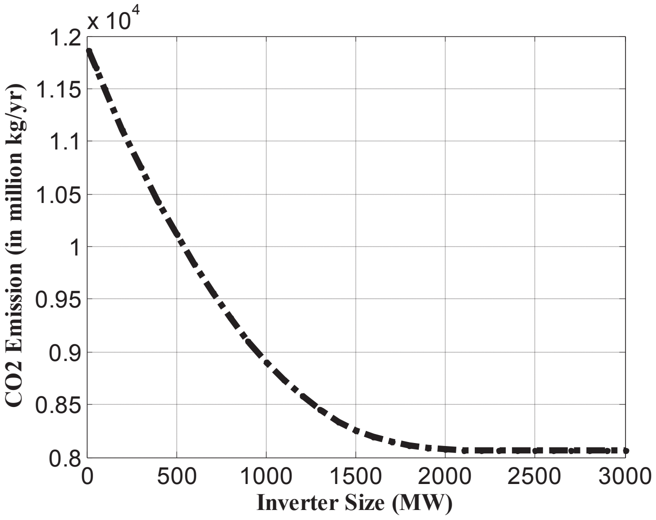


Fig. 12. CO_2 emissions vs. inverter size.

Table 4
HOMER optimization results.

	$R = 1.47$	$R = 1.00$
PV size (MW)	2200	2200
Inverter size (MW)	1500	2200
Grid (MW)	2200	2200
Initial capital (in $ million)	5000	5280
Replacement (in $ million)	1884	2144
O&M (in $ million)	15,414	15,373
Total NPC (in $ million)	21,435	21,896
CO_2 emission (in tonnes)	8,256,781	8,066,126

capacity of the PV array and the rated inverter [15]. Table 4 shows the optimization results for the two configurations.

Total NPC for $R = 1.00$ (PV and inverter size are each 2200 MW) is higher than $R = 1.47$ (PV is 2200 MW while inverter size is 1500 MW) and this can easily be noticed in Fig 10. Inverter costs (capital, replacement and O&M) are the main contribution for this high NPC, as illustrated in Fig. 13. However, the configuration of $R = 1.00$ gives no unmet load (unmet load = 0%) and no excess electricity (excess electricity = 0%). Moreover CO_2 emissions for $R = 1$ are lower than those for $R = 1.47$ configuration because for $R = 1.47$, more electricity is purchased from the grid that contributes some emissions.

Fig. 14 shows the electricity produced by a 2200 MW PV and 2200 MW inverter for $R = 1.00$. The PV arrays contribute 33% to the total electricity production.

With these real observations in mind, the optimization configuration of $R = 1.00$ is better to be applied to the grid-connected PV system in Makkah because of its effectiveness in serving the entire load though with relatively higher NPC.

6. Conclusion

Resource optimization is a major factor in the assessment of the effectiveness of renewable energy systems. Various methods are being utilized by different researchers in planning and sizing the grid-connected PV systems. In this paper, optimal PV, inverter and PV/inverter sizes for a grid-connected PV system in Makkah, Saudi Arabia have been investigated by using HOMER as a software tool. Net present cost, renewable electricity fraction, excess electricity, and CO_2 emissions are the major key performance parameters that have been considered in determining the optimal system configuration. The optimum PV array and inverter sizes for a grid-connected PV system have been obtained with the unmet load

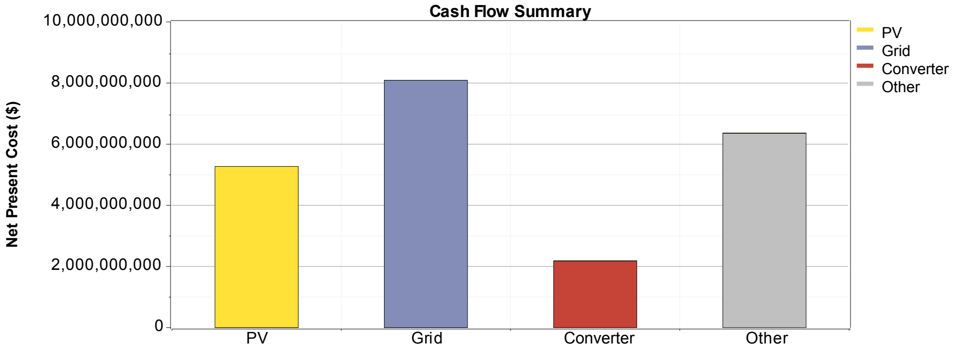


Fig. 13. Cash flow summary.

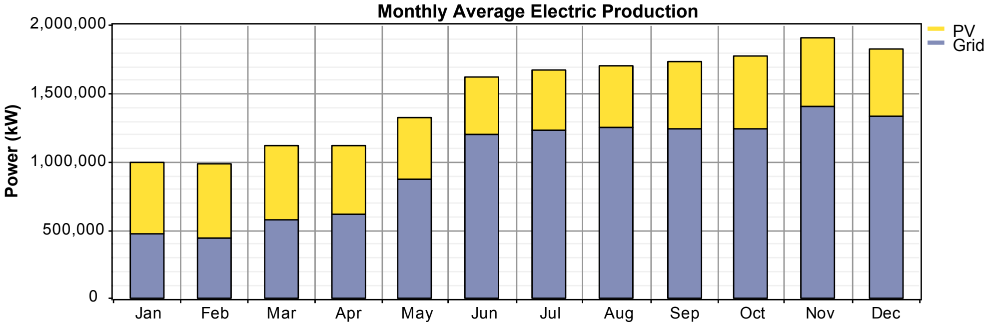


Fig. 14. Electricity production for a 2200 MW PV and a 2200 MW inverter.

and excess electricity percentages as the main constraints. An optimum system configuration, with unmet load and excess electricity of 0% for serving electricity in Makkah city with a peak load of 2200 MW, is obtained for 2200 MW PV size and 2200 MW inverter size, i.e. for the ratio of $R = 1.00$. However, the inverter size can be lower than 2200 MW if the NPC is the main factor to be taken into account when selecting the system for implementation.

References

[1] Rehman S, El-Amin IM, Ahmad F, Shaahid SM, Al-Shehri AM, Bakhashwain JM, et al. Feasibility study of hybrid retrofits to an isolated off-grid diesel power plant. Renew Sustain Energy Rev 2007;11:635–53.

[2] Deshmukh MK, Deshmukh SS. Modeling of hybrid renewable energy systems. Renew Sustain Energy Rev 2008;12:235–49.

[3] Shaahid SM, El-Amin I. Techno-economic evaluation of off-grid hybrid photovoltaic–diesel–battery power systems for rural electrification in Saudi Arabia – a way forward for sustainable development. Renew Sustain Energy Rev 2009;13:625–33.

[4] Erdinc O, Uzunoglu M. Optimum design of hybrid renewable energy systems: overview of different approaches. Renew Sustain Energy Rev 2012;16:1412–25.

[5] Dursun B. Determination of the optimum hybrid renewable power generating systems for Kavakli campus of Kirklareli University, Turkey. Renew Sustain Energy Rev 2012;16:6183–90.

[6] Jamel MS, Rahman AA, Shamsuddin AH. Advances in the integration of solar thermal energy with conventional and non-conventional power plants. Renew Sustain Energy Rev 2013;20:71–81.

[7] Kuramochi T, Ramírez A, Turkenburg W, Faaij A. Techno-economic prospects for CO_2 capture from distributed energy systems. Renew Sustain Energy Rev 2013;19:328–47.

[8] Twaha S, Al-Hamouz Z, Mukhtiar MU. Optimal hybrid renewable-based distributed generation system with feed-in tariffs and ranking technique. In: Proc. IEEE international power engineering and optimization conference; 2014. p. 115–20.

[9] Mahmoud MM, Ibrik IH. Techno-economic feasibility of energy supply of remote villages in Palestine by PV-systems, diesel generators and electric grid. Renew Sustain Energy Rev 2006;10:128–38.

[10] Batman A, Bagriyanik FG, Aygen ZE, Gül Ö, Bagriyanik M. A feasibility study of grid-connected photovoltaic systems in Istanbul. Turk Renew Sustain Energy Rev 2012;16(8):5678–86.

[11] Kaundinya DP, Balachandra P, Ravindranath NH. Grid-connected versus stand-alone energy systems for decentralized power – a review of literature. Renew Sustain Energy Rev 2009;13:2041–50.

[12] Eltawil MA, Zhao Z. Grid-connected photovoltaic power systems: technical and potential problems – a review. Renew Sustain Energy Rev 2010;14:112–29.

[13] Mellit A, Kalogirou SA, Hontoria L, Shaari S. Artificial intelligence techniques for sizing photovoltaic systems: a review. Renew Sustain Energy Rev 2009;13:406–19.

[14] Islam S, Woyte A, Belmans R, Nijs J. Undersizing inverters for grid connection – what is the optimum?. In: Proceedings of the 18th symposium photovoltaic solar-energy; 2003. p. 414–9.

[15] Burger B, Rüther R. Inverter sizing of grid-connected photovoltaic systems in the light of local solar resource distribution characteristics and temperature. Sol Energy 2006;80:32–45.

[16] Mondol JD, Yohanis YG, Norton B. Optimal sizing of array and inverter for grid-connected photovoltaic systems. Sol Energy 2006;80:1517–39.

[17] Macedo WN, Zilles R. Operational results of grid-connected photovoltaic system with different inverter's sizing factors (ISF). Prog Photovolt Res Appl 2007;15:337–52.

[18] Luoma J, Kleissl J, Murray K. Optimal inverter sizing considering cloud enhancement. Sol Energy 2012;86:421–9.

[19] Chen S, Li P, Brady D, Lehman B. Determining the optimum grid-connected photovoltaic inverter size. Sol Energy 2013;87:96–116.

[20] Hernandez JC, Vidal PG, Almonacid G. Photovoltaic in grid-connected buildings. Sizing and economic analysis. Renew Energy 1998;15(1):563–5.

[21] Mondol JD, Yohanis YG, Norton B. Optimising the economic viability of grid-connected photovoltaic systems. Appl Energy 2009;86:985–99.

[22] Orioli A, Gangi AD. Load mismatch of grid-connected photovoltaic systems: review of the effects and analysis in an urban context. Renew Sustain Energy Rev 2013;21:13–28.

[23] Qi W, Liu J, Christofides PD. A distributed control framework for smart grid development: energy/water system optimal operation and electric grid integration. J Process Control 2011;21:1504–16.

[24] Qi W, Liu J, Christofides PD. Supervisory predictive control for long-term scheduling of an integrated wind/solar energy generation and water desalination system. IEEE Trans Control Syst Technol 2012;20(2):504–12.

[25] Qi W, Liu J, Christofides PD. Distributed supervisory predictive control of distributed wind and solar energy systems. IEEE Trans Control Syst Technol 2013;21(2):502–12.

[26] Parida B, Iniyan S, Goic R. A review of solar photovoltaic technologies. Renew Sustain Energy Rev 2011;15:1625–35.

[27] Tyagi VV, Rahim NAA, Rahim NA, Selvaraj JAL. Progress in solar PV technology: research and achievement. Renew Sustain Energy Rev 2013;20:443–61.

[28] Notton G, Lazarov V, Stoyanov L. Optimal sizing of a grid-connected PV system for various PV module technologies and inclinations, inverter efficiency characteristic and locations. Renew Energy 2010;35:541–54.

[29] http://www.homerenergy.com.

[30] Murphy PM, Twaha S, Murphy IS. Analysis of the cost of reliable electricity: a new method for analysing grid connected solar, diesel and hybrid distributed electricity systems considering an unreliable electric grid, with examples in Uganda. Energy 2014;66:523–34.

[31] Hafez O, Bhattacharya K. Optimal planning and design of a renewable energy based supply system for microgrids. Renew Energy 2012;45:7–15.

[32] Twaha S, Idris MH, Anwari M, Khairuddin A. Applying grid-connected photovoltaic system as alternative source of electricity to supplement hydro power instead of using diesel in Uganda. Energy 2012;37:185–94.

[33] Lau KY, Yusof MFM, Arshad SNM, Anwari M, Yatim AHM. Performance analysis of hybrid photovoltaic/diesel energy system under Malaysian conditions. Energy 2010;35:3245–55.

[34] NASA Langley Research Center, Atmospheric Science Data Center. http://eosweb.larc.nasa.gov.