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

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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

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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

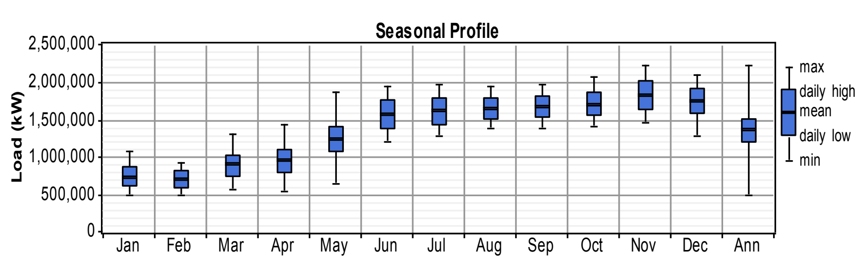

Fig. 1. Monthly load profile of Makkah.