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Original article

Techno-economic potential of largescale photovoltaics in Bahrain

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ABSTRACT

The electricity demand of Bahrain has been increasing rapidly in the recent years. At the present growth rate, the electricity peak demand is expected to reach 9500 MW by 2030. The cost of conventional generation in Bahrain, based on natural gas is comparatively high. The nature of the solar resource and energy demand in Bahrain is suggestive of large scale photovoltaics having significant potential for meeting the country's future electricity demand. The economic performance of a 1 MW grid-connected photovoltaic (PV) system optimised for matching the daily peak load in Bahrain is analysed in this work in terms of levelised cost of electricity (LCOE), net present value (NPV), payback period (PBP) and energy payback time (EPBT). Results show a positive trend indicating that large scale photovoltaics could be a viable alternative for meeting future electricity demand. Even at current PV system prices the LCOE for the system designed was 43% less than the present actual cost of a kWh in Bahrain.

Introduction

The Kingdom of Bahrain is a small GCC (Gulf Corporation Council) country in the MENA (Middle East and North Africa) region which has one of the best solar insolation conditions in the world. The energy consumption in Bahrain is increasing rapidly. The peak demand for 2015 was 3.4 GW and the average peak demand growth rate was around 7% for the last ten years [1]. The peak demand is expected to reach 9.5 GW by 2030 which means that Bahrain will need to more than double the existing power generation capacity in the coming 10–15 years. Total installed power capacity of Bahrain is 4 GW, all of which depend on natural gas as the fuel for generation. It is worth mentioning that the consumer electricity prices in Bahrain are highly subsidised. The actual cost of a kWh is 28 fils ($ 0.074) while the consumer pays 3 fils if their consumption is below 3000 kWh/month, 9 fils if it is below 5000 kWh/month and 16 fils if the consumption is more than 5000 kWh/month [2]. The total dependence on natural gas alone is not sustainable in the long run especially considering the high gap between the actual cost of electricity and the revenue from consumers. Bahrain needs to invest in more sustainable and cheaper energy sources.

The most widely utilised renewable energy resources in the world are wind and PV. Wind energy leads the renewable energy market with a share of 55.2% followed by PV with a share of 28.9% [3]. The countries that lead this growth are China, the United States, Japan and Germany which accounts for 70% of the total installed capacity [4]. Even though PV is an ideal candidate given the regions high annual irradiation, the countries in the MENA region are yet to have a significant PV uptake. In contrast, there has been a dramatic increase in the global uptake of large-scale grid-connected PV in the last few years due to factors such as falling prices and developments in large scale manufacturing [5].

In the literature, various authors have explored the techno-economic feasibility of either PV hybrid systems (in combination with another generation such as wind, diesel etc.) [6–8] or standalone PV systems [9,10], in middle-eastern climates. The techno-economics of PV systems for specific applications such as water pumping and desalination is explored in [11,12]. However, the number of studies examining the techno-economic feasibility of large-scale grid-connected PV systems in the Middle East is limited and none in particular for Bahrain. Authors of [13] investigated 29 locations in Egypt to site a 10 MW grid-connected PV plant. The study found that the lowest Levelised Cost of Electricity (LCOE) of 0.199 $/KWh was obtained for the location Wahat, Kharga. It was identified in [14] that an LCOE of 0.16 $/KWh can be achieved for a 1 MW PV power plant in Kuwait, if the system price was $4/W. The authors of [15] focus on a utility scale PV project of 100 MW in the United Arab Emirates (UAE), the study found out that using SdTe panels with 1-axis tracking at a cost of 1.8 $/W for the PV system, the mean value of LCOE will be 0.1769 $/KWh.

From the electric power network perspective, it is of vital importance that any generator considered for accommodating future load growth is able to match peak demand. The system load curve, the

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conventional generation system and electricity pricing schemes are unique to Bahrain and quite distinctive from other nations having similar climates. Other studies in the literature consider the techno-economics of grid-connected PV for similar climates, with fixed capacities [16] or sizing optimised for energy yield or economics or installations constraints (e.g. building integration) [17]. There is little work reported on the techno-economics of systems optimised for peak demand. The aim and major contribution of this is paper is the determination of the economic viability of implementing a large scale grid-connected PV system with its orientation optimised to coincide the temporal peak of the daily system load curve, in Bahrain. The viability analysis is conducted in terms of 4 parameters: LCOE, Net present value (NPV), Payback period (PBP) and Energy payback time (EPBT). The results are expected to inform utility policies and investments in Bahrain.

The rest of the paper is organised as follows: Section "Methodology" describes the location selection, PV input data and system modelling along with the economic analysis methodology; results of the analyses are presented and discussed in Section "Results and discussion"; finally, conclusions are drawn in Section "Conclusions".

Methodology

PV system design and simulation

The solar resource assessment tool PVGIS (Photovoltaic Geographic Information System) from JRC (EU Joint Research Centre, Ispra) was used to identify the location in Bahrain with the best solar resource. The town of Zallaq (latitude 260 21′ N and longitude 500 49′ E) had the highest potential with an irradiation of 6250 Wh/m^2/day. A PV system size of 1 MW was chosen for this study. The PV technology selected was poly-crystalline. Dusol modules were chosen for the design as they have started manufacturing facilities in GCC which will make it easier to source their modules. For grid integration, instead of using a single large inverter with capacity of 1 MW, 5 SMA Sunny Central inverters with a capacity of 200 kW each was used, the idea is to avoid operating inverter in its low efficiency regions when the output from PV array is low.

PVsyst software (V6.39) was used for design and optimisation of the PV system operation. PVsyst is an industrial standard software that has been validated for different climates and PV module and inverter technologies [18–20]. The software has facility to input meteorological data manually as well as import data from different databases. PVSyst considers a number of parameters affecting PV generation and can simulate the annual energy generation of a potential project site [21]. The 1 MW PV system was simulated in PVsyst for the Zallaq region in Bahrain. The meteorological data for the location was collected by a satellite based GIS (Geographical Information System) system: PVGIS Climate –SAF (Photovoltaic Geographical Information System Climate Monitoring Satellite Application Facility). The data was imported from PVGIS Climate-SAF database to PVsyst to validate the sizing of the grid-integrated PV system and to understand the system performance.

In the Northern hemisphere, the collector plane of the PV array needs to be oriented to face south (azimuth 0°) and placed at a specific tilt angle to receive maximum solar radiation. It was found from PVsyst simulations that maximum output can be achieved from the PV array used in this study by choosing a tilt angle of 25° and azimuth angle of 0°. However, one of the objectives of the system design was to achieve temporal coincidence of system peak load and PV generation peak. It was observed from the load profile of Bahrain that the peak load occurs between 1:00 P.M. and 4:00 P.M [22]. The generation peak for a PV design with a tilt angle of 25° and azimuth angle of 0° does not match the load peak. Changing the azimuth and tilt angles of the PV array to 35° and 50° respectively results in peak PV generation matching the load peak. The main parameters and outputs from the PVsyst system simulation are presented in Table 1.

Table 1
The main parameters of the 1 MW PV system.

Parameters	Value
PV module technology	Polycrystalline Silicon
PV array total P_{nom}	1001 kWp
Cell area	6083 m^2
Inverter Nominal Power	200 kW (ac)
No. of inverters	5
Produced Energy	1641 MWh/year

Degradation rate and system lifetime

The amount of energy generated by the PV system over its lifetime depends on its annual degradation rate. The annual degradation rate is very important in the economic viability analysis, because choosing a higher degradation rate will lead to a lower estimate of generated power and consequently reduced cash flow in the future. It was found that the actual in-field annual degradation rate for crystalline silicon PV cells is between 0.2 and 0.5% [23]. In this study, an annual degradation rate of 0.5%/year was considered.

The system lifetime is equally important as the degradation rate. A lower degradation rate and longer system lifetime can increase the reliability of the system and will lead to reduced LCOE. Presently a more standard expectation of lifetime is 30 years for the system with 15 years inverter lifetime [24]. Fig. 1 shows the produced energy over the lifetime of the PV system. The total energy production of the system will be 45,822 MWh with an average annual production of 1527 MWh.

PV economic evaluation

The main concern with a PV installation is that the costs must be recovered by means of sales of the energy generated by PV system during its lifetime. In addition to the PV module cost, the cost of mounting, wiring and installation which is called as Balance of System (BOS) and inverter cost should be considered in the calculation of the total cost of the system [24]. The breakdown of the installation cost of the 1 MW PV system is shown in Table 2. The parameters used for the economic evaluation and the calculation methodology are detailed in the following paragraphs.

Levelised cost of electricity (LCOE)

LCOE is as a long-term guide to competitiveness of energy generation technologies. The LCOE methodology is often used as a ranking tool as it can remove biases between technologies and assess the cost-effectiveness of different power generation technologies [25]. The LCOE can be calculated as a ratio of the total life cycle cost to the total lifetime energy production by the PV system as per the following equation [26]:

$$LCOE = \frac{Anual\ Cost + O\,\&\,M}{Annual\ Energy\ produced\ by\ the\ system} \tag{1}$$

where O&M is the operation and maintenance costs.

To calculate the annual cost of the system, a Capital Recovery Factor (CRF) which converts the present value of installation cost of the system into an equal annual cost over the period of the system lifetime, is used. So, the equation can be presented as [14]:

$$LCOE = \frac{(Installation\ Cost \times CRF) + O\,\&\,M}{Annual\ Energy\ produced\ by\ the\ system} \tag{2}$$

where CRF is given by the equation:

$$CRF = \frac{i \times (1+i)^n}{[(1+i)^n - 1]} \tag{3}$$

where i is the annual real interest rate and n the lifetime of the system. The annual real interest rate is an interest rate after accounting for