Assessing the Technical Impact of Integrating Largescale Photovoltaics to the Electrical Power Network of Bahrain

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Highlights

1. Potential grid integration impacts of largescale PV in Bahrain is investigated.

2. Optimum location for PV installation in Bahrain is identified.

3. Feasibility of system design to match PV generation with peak load is investigated.

4. Impact of Bahrain's weather conditions on PV system operation is examined.

Abstract

Electricity demand of Bahrain is met almost entirely by gas turbine power stations at present. The peak demand growth rate of around 6.5 % per year necessitates installing new generation in near future. Bahrain's rich natural solar resource could be exploited to meet this need. However, so far, no detailed studies on the grid integration of large scale photovoltaics (PV) systems have been carried out. Potential impacts of integrating a 1MW PV plant to the power network of Bahrain is examined in this paper by means of a systematic modelling analysis using PVsyst and PSSE. Results demonstrate how PV systems can exploit the advantage provided by the weather of Bahrain to match the peak demand. Other concerns addressed in this work are impact of PV generation during times when electrical power network is more susceptible to voltage limit violations and impact of fault current contribution from the PV plant to the security of the network considered. The overarching view from the results of these grid integration studies is that the outlook for network integrated PV in the future In Bahrain is positive. It is hoped that the results of this work would inform Bahrain's utility's policies on PV systems.

Keywords

Photovoltaics; grid integration; power flow; fault analysis

Abbreviations and nomenclature

EWA – Electricity and Water Authority, Bahrain
PV – Photovoltaic
GCC – Gulf Co-operation Council
PVGIS – Photovoltaic Geographical Information System
GHI – Global Horizontal Irradiation
JRC – Joint Research Centre of the European Commission
STC – Standard Test Conditions
NOP – Normal Open Point
RMU – Ring Main Unit
LV – Low Voltage
PR – Performance Ratio
I – Current supplied by PV module (A)
I_{ph} – Photocurrent (A)
I_O – Inverse saturation current depending on the temperature (A)
q – Charge of an electron (C)
V – Voltage at the terminals of the module (V)
R_S – Series resistance (Ω)
N_{CS} – Number of cells in series
γ – Photodiode quality factor
k – Bolzmann's constant (J/K)
Tc – Effective cell temperature (K)
R_{sh} – Shunt resistance (Ω)
G – Effective irradiance (W/m²)
G_{ref} – Reference irradiance (W/m²)

μI_{SC} – Temperature coefficient of photocurrent (short-circuit current) (/°C or /°K)
$T_{C\ ref}$ – Reference cell temperature (K)
E_{Gap} – Energy gap of the semiconductor material (eV)

Introduction

Bahrain is a country where the electricity demand is growing. The annual electricity demand rapidly increased in the recent years and reached a 10% growth rate in 2014. A large portion of the demand is due to the domestic sector which accounts for about 48% of the annual electricity demand. In addition, the peak load of Bahrain which normally occurs between June and September reached 3335 MW for 2015 with a growth rate of 5.8% over the previous year (EWA, 2015; Information & eGoverment Authority, 2015). An increasing in the electricity demand means that the generation capacity has to be expanded to keep pace with it. Bahrain has five power generation plants with capacity of around 4 GW, all of which depend on gas as the fuel for operation. An increase in the amount of gas turbine power stations will result in increased in CO_2 emissions (Rehman and El-Amin, 2012).

The GCC is made up of six major oil and natural gas producing countries namely Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates. Recently, the countries of GCC have started introducing serious plans to increase the number of renewable energy projects in order to diversify their energy resources both in technical and economic terms and help them towards sustainability by improving energy efficiency and reducing CO_2 emissions (Griffiths and Mills, 2016; Bouhouras et al., 2010). Bahrain has already announced a plan that by year 2020 the contribution of renewable energy to electricity generation will be 5% of the total generation capacity. Solar energy has received more attention as compared to other renewables (Bhutto et al., 2014). This is a step in the right direction as the cost of traditional electricity production in Bahrain - 28 fils per kWh (0.07 USD/kWh) which compared to the average levelised cost of PV generation from GCC countries (0.05 - 0.10 USD/kWh) is actually more expensive (IRENA, 2016). In comparison the cost of generation for Saudi Arabia is 0.099

USD/kWh and Kuwait is 0.0133 USD/kWh (Sharples and Radhi, 2013) which makes the former more attractive and latter less attractive for PV as compared to Bahrain.

The Middle East and North Africa region where Bahrain is situated has some of the best of solar insolation in the world. The average daily solar radiation of GCC countries alone is about 6 kWh/m^2 with more than 80% clear sky during the year (Alnaser and Alnaser, 2011). It is clear that the countries with high irradiation like Bahrain has a good opportunity to invest in photovoltaic (PV) technology (Singh, 2013). PV systems have very low maintenance cost compared to conventional generation because of the reduction in the number of moving parts (Alnaser, 2015). Another main advantage of PV is its modularity which makes its applications easier and more widespread in the end-user market (Mansouri et al., 2013). The cost of manufacturing PV modules is following a decreasing trend and is expected to decline more in the coming years (Li et al., 2012). The low maintenance cost, lowering cost of modules and CO_2 emission free nature of PV systems should promote PV installation in countries like Bahrain which a high electricity generation has cost and considers the climate change problem seriously.

Many studies exploring the electricity generation potential, economic viability and CO_2 emission reduction capacity of PV systems have been conducted for different countries in the GCC region. Mansouri et al. (2013) looked at the case of Saudi Arabia in the context of growing energy consumption and consequent CO_2 emissions and examined the emission reduction potential of PV systems along with carbon capture and storage. Reiche (2010) comments on the energy policies of GCC countries and demonstrates how they have recently adopted a more pro-active approach toward addressing environmental issues in their energy sectors. Radhi (2011) examined the value of smaller scale building integrated de-centralised PV systems for GCC and highlights the need for financial incentives to promote their uptake. Alnatheer (2005) shows how expanding electricity generation by including wind and PV systems can result in a societal least-cost plan for Saudi Arabia. For Bahrain, given the already high generation cost compared to Saudi the impact on the societal cost should be much more positive. Ramadhan and Naseeb (2011) examined the costs and benefits of PV systems in Kuwait and demonstrated that the true economic cost of a unit of energy from PV systems will decline significantly when the savings in conventional generation and the cost of reducing CO_2 emissions are accounted for. The technical and economic potential of PV systems for the climate of countries in GCC was assessed in (Abdullah et al., 2002) (Harder and Gibson, 2011), (Sharples and Radhi, 2013).

The policy options for renewable energy was examined in (Mezher et al., 2012) for Abu Dhabi and highlights the importance of taking into consideration both electricity generation and demand which is taken care of in this study. The development of an integrated resource planning framework for expanding Saudi Arabia's electricity generation option was presented in (Alnatheer, 2006). The author highlights the need for the availability of renewable energy technology potential assessments for using in generation expansion planning. One of the reasons for the lower number of PV potential assessments was the need to formulate solar resource estimation methodologies, an example of this, for Saudi Arabia, is presented in (El-Sebaii et al., 2009). This difficulty was alleviated to a large extent with the availability of PVGIS which is used in this study. Unlike using independent PV potential estimation software such as HOMER, RETScreen, System Advisor Model etc. in combination with a solar database such as NREL, NASA etc. PVGIS is a geographic information system that does an integrated mapping of data essential for PV resource estimation (climate, estimated solar electricity generation, optimum inclination angle of the PV modules) into one online tool.

The design of a pilot 36 kW PV system and observations from its first year of operation integrated to the low voltage (0.4 kV) network of Abu Dhabi is reported in (Al-Sabounchi et al., 2013a). The negative effect of weather conditions of the location especially accumulated dust deposition on the PV system power outputs was demonstrated. The performance PV system under the weather of Doha is examined in (Touati et al., 2016) using a customized measurement and monitoring system. They point out the impact of relative humidity in addition dust on the efficiency of PV generation.

The system design, specifically optimal sizing of the grid-connected PV inverter with respect to the size of the PV array was discussed in (Ramli et al., 2015) with regards to unmet demand, surplus generation, fraction of renewable electricity, net present cost and CO_2 emissions for Saudi Arabia. Al-Sabounchi et al. (2013b) looked at the potential impacts of integrating PV systems to the electrical power network of UAE base on two pilot systems rated at 36 kW and 9 kW and highlighted the importance of basing the PV system location and size based on the electricity demand profile and the PV generation profile. Despite similar solar resources, the type of main conventional generation plants, network configuration, cost of generation transmission and distribution varies from country to country. There were no studies in the literature which specifically looked at the potential impacts of integrating large scale PV systems to the electrical power network of Bahrain. The research presented in this paper aims to address this gap in knowledge.

Not withholding its positives, the design and network integration of PV systems especially at the large scale is not without challenges and ambiguities. The warm climate and the high temperature at the PV module surface may lead to a decrease in the module performance (Grossmann et al., 2013). PV generation operates in a direction opposite that of conventional power flow this may result in changes to network voltage profiles and in certain cases violation of node voltage limits, a reduction or an increase in line losses, and increased fault current levels (Barker and Mello, 2000). Thus, the integration of large scale PV systems to electrical power networks, could have positive or negative impacts on the network depending on the network configuration and the solar resource of the location. In order to formulate appropriate policies and guidelines, utilities and government agencies require data on the impacts of network integration of PV systems under the climate of the country. Installation of PV systems in countries like Bahrain with load peaks in the afternoon offer the opportunity for using PV generation for natural daily peak load matching. There were no detailed studies done so far to assess the impact of network integration of large scale PV systems in Bahrain. The potential impacts of integrating a 1MW PV plant to the power network of Bahrain is examined in this paper by means of a systematic modelling analysis using PVsyst and PSSE. The main objective of this work is to inform the design of large scale PV systems in Bahrain and the utility policies on network integration of these systems.

2. Methodology

The first step in the analysis will be the identification of the region with best PV generation potential from selected regions. Region with the highest PV generation will be the worst case for power networks due to power flow in the reverse direction (from the load side to the generation side). The feasibility of designing a 1 MW large scale PV system optimised for afternoon peak load matching without compromising on energy yield will then be investigated. Performance ratio will be used as the metric to determine feasibility. This will be followed by scenario based analyses of the impact of integrating the 1 MW PV system to the electrical power network of Bahrain in terms of Power flow and network losses, Seasonal voltage profiles and PV system fault current contribution.

2.1. Electricity demand of Bahrain

As mentioned earlier presently, Bahrain has five power generation plants with capacity of around 4 GW. One of the important factors in design of new electrical energy generation plants is the knowledge of the demand profile of the power system that the new generation plant should meet (Karki et al, 2012). Every year the peak demand occurs in the summer between July and September because of heavy usage of air conditioners. It is observed from the data recorded for the previous years that the growth rate of system peak load is around 6.5 %. Fig. 1 shows the peak load growth for last ten years.

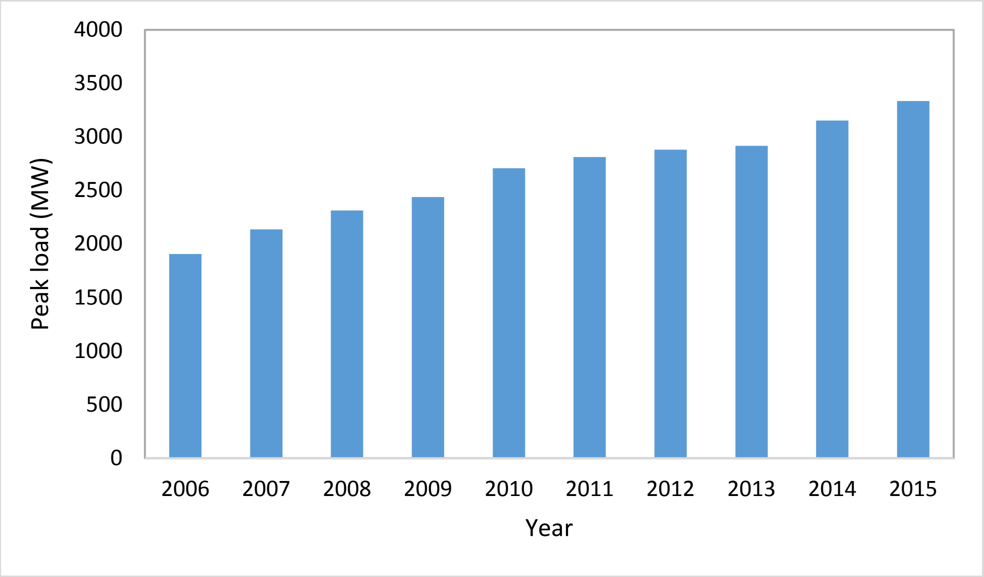

Fig. 1. Peak load growth

Fig. 2. Shows Bahrain's system load profile for the peak and minimum demand days. The peak demand, during summer months, occurs between 1:00 P.M. and 3:00 P.M. Meanwhile, the minimum demand condition occurs between January and February. The load profile of the minimum demand day indicates that there is a huge difference of around 60 % in the energy consumption between the peak and minimum days. Furthermore, the load peak for the minimum demand day occurs after sunset between 5:00 P.M. and 7:00 P.M.

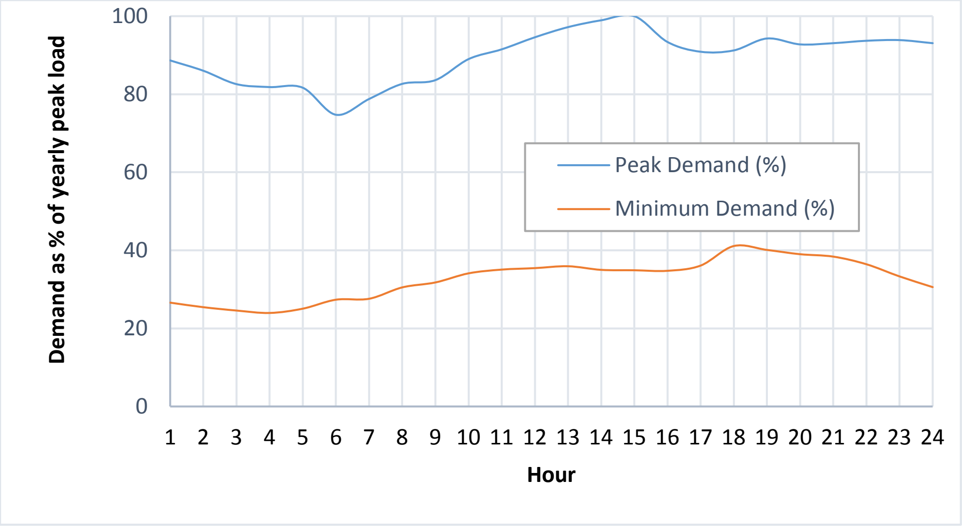

Fig. 2. Load profile of peak and minimum demand days

2.2. Solar resource of Bahrain and location selection

Being located in the GCC region, Bahrain receives high amount of solar irradiation especially during summer months. Fig. 3 shows the distribution of the monthly average (1985-2004 averages) daily Global Horizontal Irradiation (GHI) received and ambient temperature. The average monthly temperature of Bahrain reach around 34.2 ^{o}C. The daily average sunshine duration for Bahrain is around 9.2 hours and it reaches to about 13.7 hours in summer (Rehman and El-Amin, 2012; Alnaser and Alnaser, 2011). The monthly sunshine duration is highest in June at 335 hours/ month and the lowest in January at 221 hours/month. The average duration is 275 hours/month (Sharma and Chandel, 2013), which justifies the use of this energy for MW scale PV systems.

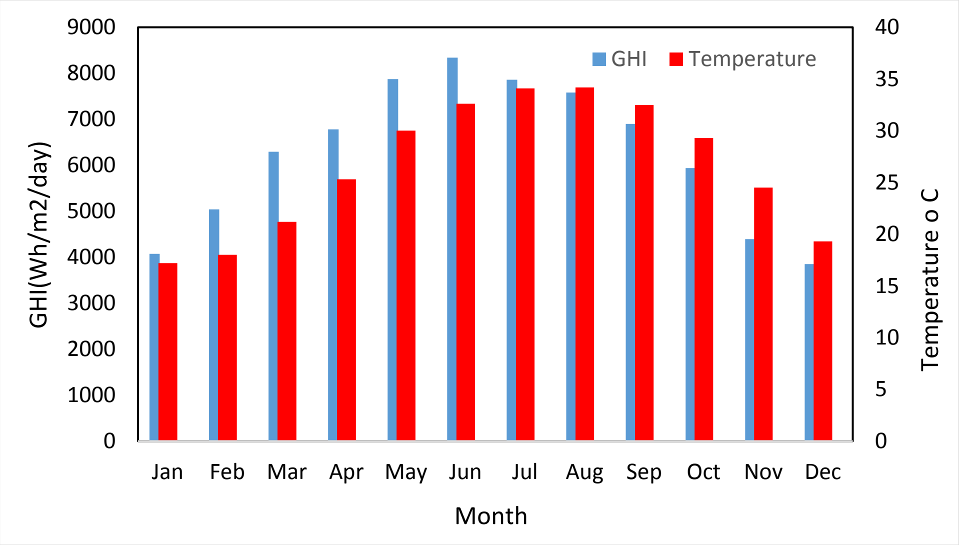

Fig. 3. Monthly average solar irradiation and temperature

The location with the highest PV generation potential will be the worst case for electrical power networks due to power flow in the reverse direction. Network security and reliability can be assured if the impact of worst case generation is within network operational limits. There are many factors that affect the amount of solar radiation reaching the PV array surface such as the day of the year and the latitude (Eltawil and Zhao, 2010). In order to select the best location for the project, 19 locations were chosen from the map of Bahrain. PVGIS is a web-based calculator developed by the JRC (Joint Research Centre) of the European Commission based on years of recorded data using satellites. PVGIS can provide a mapping of the solar radiation potential of a certain area, based its solar radiation database (Joint Research Centre, n.d.; PVsyst., 2014). Annual average daily solar irradiation was calculated for all the locations chosen using PVGIS. The results are shown in Table 1. It is cleared from the results that the location no. 9 (Latitude 26.021^0 N and Longitude 50.49^0 E) the town of Zallaq has the highest yearly irradiation input. Zallaq is located in the south west of Bahrain as shown in Fig. 4.

Table 1. Average daily solar irradiation of the chosen locations

No.	Latitude	Longitude	Wh/m^2/day
1	25.881	50.60	6020
2	25.881	50.57	5910
3	25.881	50.53	5940
4	25.951	50.60	5980
5	25.951	50.55	5820
6	25.951	50.47	5970
7	26.021	50.62	5930
8	26.021	50.56	5860
9	**26.021**	**50.49**	**6250**
10	26.091	50.61	5830
11	26.091	50.56	5880
12	26.091	50.49	6230
13	26.161	50.62	5970
14	26.161	50.54	6020
15	26.161	50.49	5970
16	26.231	50.59	5590
17	26.231	50.56	6190
18	26.231	50.45	6200
19	26.21	50.67	6010

Fig. 4. Location of Zallaq in Bahrain

2.3. System modelling

2.3.1. PV model

The ‘one diode’ model of PV modules was used in annual energy simulations for modelling PV modules using PVsyst software. Fig. 5 shows the equivalent circuit of this model.

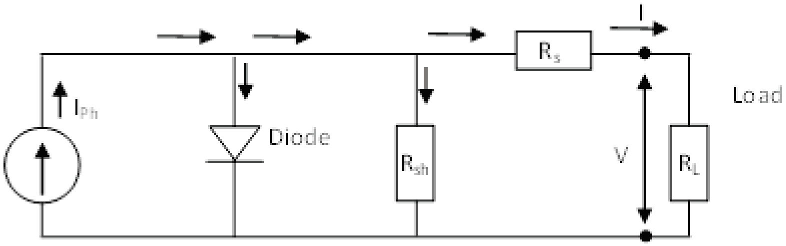

Fig. 5. The equivalent circuit for a PV module

The equation describing the equivalent circuit is as follows:

$$\boldsymbol{I = I_{ph} - I_O\left[e^{\left(q\times\frac{V+I\times R_S}{N_{CS}\times\gamma\times k\times T_C}\right)} - 1\right] - (V + I\times R_S)/R_{sh}} \qquad (1)$$

Equation (1) depend on the incident solar irradiance, the cell temperature, and on the operational parameters which are provided by the PV modules manufactures. The model assumes that the photocurrent is proportional to the irradiance and its variation with temperature is low and positive (i.e. the μI_{SC} parameter is of the order of +0.05 %/°C). So, I_{ph} will be determined with respect to the values at the reference conditions (G_{ref}, T_{ref}) as follows:

$$\boldsymbol{I_{ph}} = \left(\frac{\boldsymbol{G}}{\boldsymbol{G_{ref}}}\right) \times [\boldsymbol{I_{ph\,ref}} + \boldsymbol{\mu I_{SC}} \times (\boldsymbol{T_C} - \boldsymbol{T_{C\,ref}})] \qquad (2)$$

The diode's reverse saturation current I_O is vary with the temperature as follows:

$$\boldsymbol{I_O} = \boldsymbol{I_{O\,ref}} \times (\frac{\boldsymbol{T_C}}{\boldsymbol{T_{C\,ref}}})^{3} \times \boldsymbol{e}^{[\left(q \times \frac{EGap}{\gamma} \times k\right) \times \left(\frac{1}{T_{C\,ref}} - \frac{1}{T_C}\right)]} \qquad (3)$$

Where E_{Gap} is the energy gap of the material [1.12 eV for crystalline Si] (Ciulla et al., 2014). PVsyst has an in built model for estimating the cell temperature T_C based on the ambient temperature input for the location investigated. Similar built in models within PVsyst estimates equivalent circuit parameters such as I0, Rs, Rsh etc. based on the PV module specifications (Appendix A1) inputted.

2.3.2. Electrical configuration of PV system

A PV system size of 1 MW was chosen for this study. 3450 Dusol poly-crystalline silicon modules of 290Wp was required to achieve this capacity. They were arranged in 290 strings of 15 modules each. Dusol modules were chosen for the design as they have started manufacturing facilities in GCC which will make it easier to source their modules (Energy.sourceguides.com, 2017). The electrical specification of a typical Dusol PV module used under STC (Standard Test Conditions) is given in the Appendix (Table A1).

Typically, in the Northern hemisphere the PV array needs to be oriented to face south (azimuth 0°) and placed at a specific tilt angle to receive maximum amount of 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, as mentioned earlier, one of the objectives of the paper is to demonstrate the possibility of natural peak load matching by optimizing the system design towards that target. It is observed from the load profile of Bahrain that the peak load occurs between 1:00 P.M. and 4:00 P.M. The generation peak of a design with tilt angle of 25º and azimuth angle of 0º does not match the load peak. Changing the azimuth and tilt angles of the PV array has to 35º and 50º respectively results in matching peak PV generation to the load peak.

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 will be used, the idea is to avoid operating inverter in its low efficiency regions when the output from PV array is low. With this configuration one inverter is set as master and other four inverters are set as slaves. The master inverter switched on first and when PV generation exceeds a certain threshold the second inverter (first slave) is switched on and with further increase in array output and so on until it reaches the fifth inverter. When PV array outputs reduce the slave inverters automatically disconnect. The technical data of the inverter is given in the Appendix (Table A2).

2.3.3 PV system simulation

PVsyst software is used for simulating PV system operation in this study. PVsyst is and industrial standard software used by engineers, researchers and architects. The software has facility to import meteo data form many different databases, as well as manually input data. PVSyst considers a number of parameters affecting PV generation and can simulate the annual energy generation of a potential project site (Djurdjevic, 2011; Gómez, López, and Jurado, 2010; Almasoud and Gandayh, 2015). The PV system design mentioned above was simulated in PVsyst (V6.39) with meteorological data of Zallaq imported from PVGIS to validate the sizing of the grid-integrated PV system and to understand the system performance. The orientation of the array collector plan is assumed as 50º with respect to the horizontal (tilt angle) and the azimuth angle as 35º. The simulation parameters for the grid-integrated PV system is taken from the technical datasheets of the PV module and inverter mentioned earlier (Tables A1 and A2). The dusty weather conditions of Bahrain is suggestive of an increased PV module soiling loss. Extensive field monitoring is required to estimate the percentage soiling loss due to dust deposition. Due to the lack of availability of concrete field monitoring data decreasing module performance due to dust deposition have not been taken into account in the PV simulations.

2.4. Network integration

Since the PV system capacity is 1 MW, it is preferred to connect the system to the 11kV distribution network (IRENA, 2016). The distribution system of Bahrain is feed by 11kV buses from 66/11kV substations. The distribution system is operated as a radial system with loops containing one Normal Open Point (NOP). The 11kV feeders are interconnected through 11kV ring main unit (RMU) type switchgear. The single line diagram of the system is shown in Fig. 6. Majority of the 11kV (LV) substations in Bahrain's distribution system have one 11kV (LV) transformer with a rating of 1,000kVA (ESB International, 2010).

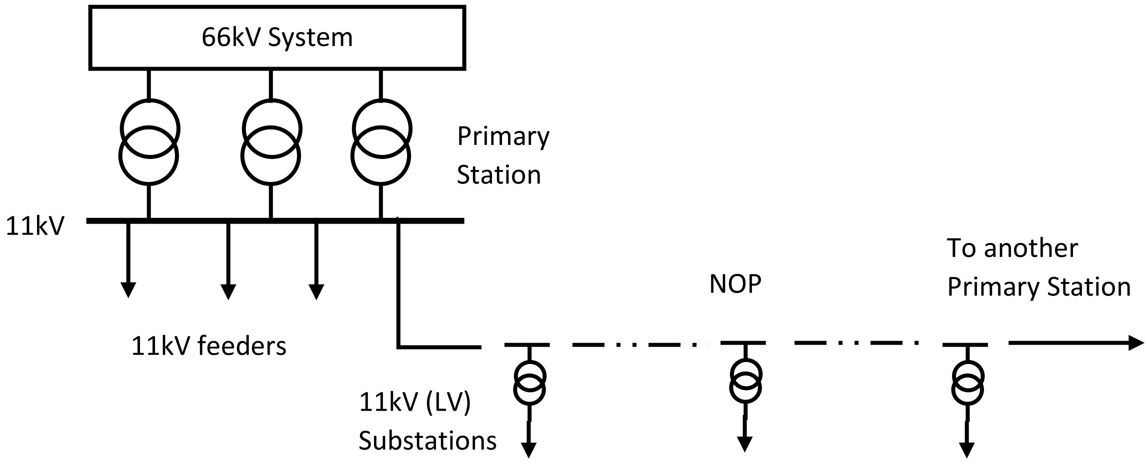

Fig. 6. Bahrain's distribution system -Typical primary substation single line diagram

2.4.1 Simulation of network integrated PV operation

PSSE (registered tradename PSS®E) is an industrial software used for simulating, analyzing, and optimizing power system performance. Since its introduction in 1976 it has become the most widely used commercial program of its type. The simulation program consists of comprehensive transmission system planning including optimal power flow and transient stability analysis (Mohamad et al., 2011). It also provides probabilistic and dynamic modeling features. PSSE was used in this work to model the electrical power distribution system of Bahrain. As mentioned earlier the network integration of PV system can bring positive or negative impacts to the power network. In order to identify the impact of point of connection of PV system to the network, a number of connection location scenarios at the 11kV network level are implemented in this study. Fig. 7 shows the single line diagram of the network arrangement from a typical 11 kV distribution substation. Table 2 summarize these point of connection scenarios considered.

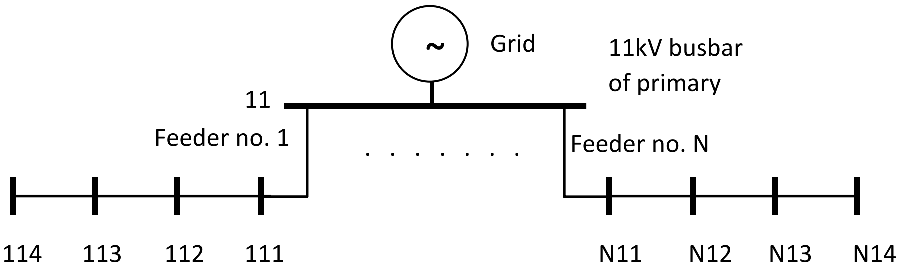

Fig. 7. Representation of the network configuration from an 11kV distribution substation

Table 2. Summary of different connection point scenarios

Scenario	Description
1	Base case (without PV system)
2	PV system connected to the bus no. 11 (11kV busbar at distribution substation)
3	PV system connected to the bus no. 111
	PV system connected to the bus no. 112
5	PV system connected to the bus no. 113
6	PV system connected to the bus no. 114

Initially power flow studies is conducted using PSSE for the scenarios considered to identify the active and reactive power flow in the network, the voltage at every node and the network losses. Two power flow studies are conducted for all scenarios: using peak demand data in summer and minimum demand data in winter along with the respective seasons PV generation. Reverse power flow will be high when PV generation is high and load is low. Seasonal voltage profiles are generated based on power flow results. In order to understand the impact of the PV system on the security of the power network a three phase short circuit fault analysis is also conducted.

3. Results and discussion

3.1. Monthly energy generation from the PV system

Based on PVsyst simulations the potential annual energy yield from the 1MW PV system designed for Zallaq is 1641.1 MWh. Fig. 8 shows the variation in the monthly energy generated by the PV system. According to Fig. 3 (section 2.1) the solar irradiation input is the highest in June and July, but so is the temperature. The impact of the high temperature of these months is clearly visible from Fig. 8. June and July has the lowest generation of all months despite the high irradiance. This clearly demonstrates the harsh impact of the environment on PV generation. Given the wastage of energy economic feasibility of forced cooling of largescale PV plants during summer is something worth investigating for Bahrain. The monthly energy generated by the PV system in low temperature months December and January is obviously low to the low solar irradiation input.

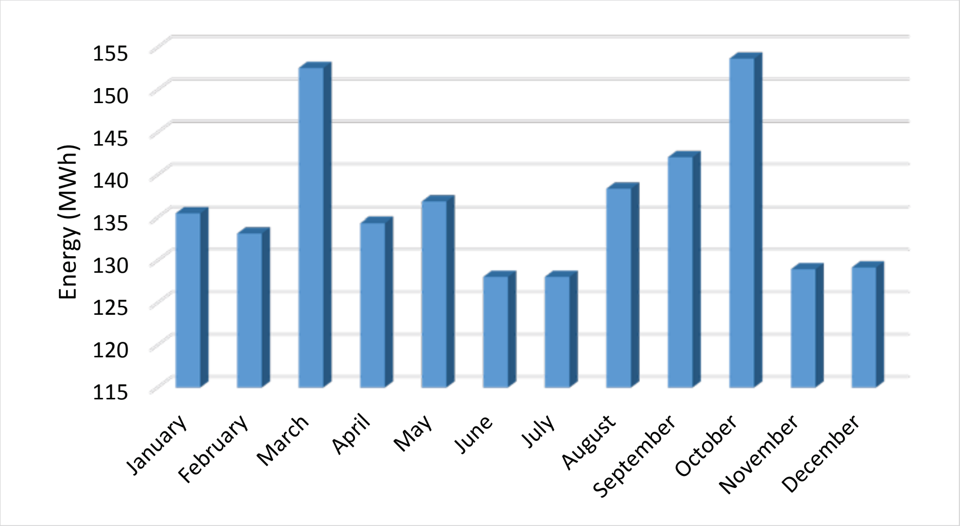

Fig. 8. Monthly energy generation by the PV system

The impact of system design, to match the peak load and peak PV generation timing, on the PV generation profile (for summer) is shown in Fig. 9. As mentioned in (section 2.3.2) the azimuth and tilt angles of PV panel was changed and the new peak PV generation time is 1:00 P.M. instead of 11:00 A.M. It is observed from Fig. 9 that the reduction in peak PV output due to time shifting is about 5% (40 kW). There is also a reduction in the total generation over the day by about 5%. Even though the reduction in energy output will have a small negative effect on the financial returns from PV, there is significant gain for the network in terms of avoidance of voltage rises, reduction in network losses and the generation reserve requirement.

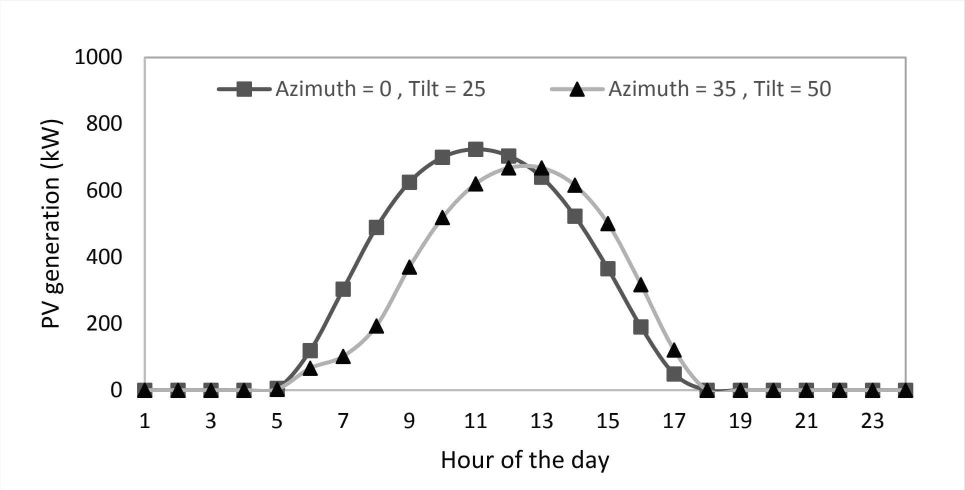

Fig. 9. Hourly PV generation profile for August

In PV system performance studies performance ratio (PR) is used a location independent measure of the efficiency of a PV system. It the ratio of the actual energy yield from a PV system to the theoretical yield possible from it. The closer the PR to 100%, the more efficient the PV system. A PR of 100% cannot be achieved because of unavoidable losses such as thermal and conduction losses. For a system located in a high temperature region a PR greater than 70% indicates high system efficiency (Chrosis, 2012). The monthly variation in the PR of the 1MW system designed for Zallaq is shown in Fig. 10. The PR results indicate that it is certainly feasible to design largescale PV systems optimised for peak load matching in Bahrain. The annual PR is about 74.2%, with its lowest value in July at 70.4% and the highest value in January at 79.4%. The impact of higher summer temperatures of Bahrain is clearly visible from the PR results.

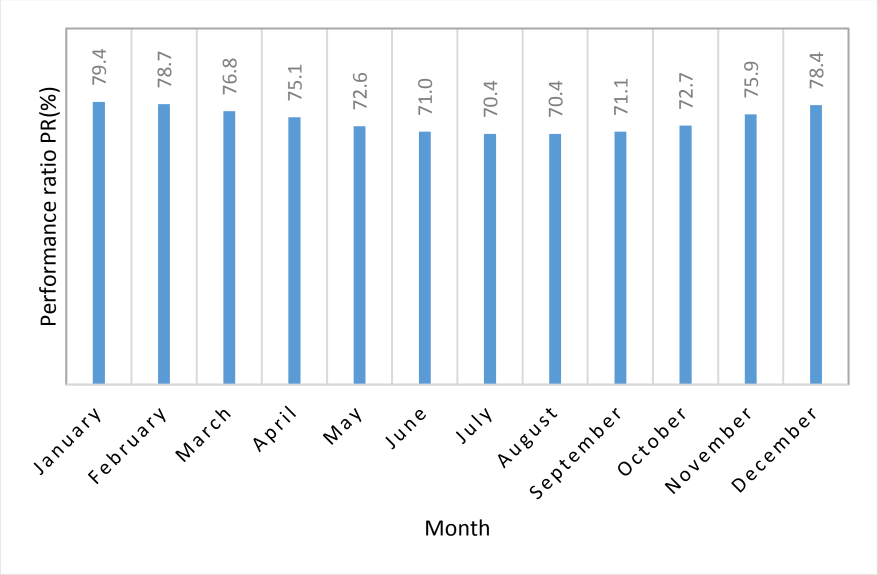

Fig. 10. Monthly Performance Ratio of the PV system

3.2. PV generation – consumer demand dynamics

All scenarios except the base case scenario 1 (Table2) considers the network integrated operation of the PV system. There is a dynamic interaction between PV generation and the consumer demand (load profile). For this work it is assumed that the load profile at the distribution substation follows the overall system load profile of Bahrain. This leads to a base load of 706 kW for summer and 255 kW for winter.

Fig. 11 and 12 shows the PV systems generation profile in summer and winter respectively verses the load profile of the distribution substation. The figures shows the dynamic interaction in terms of grid imports and exports (negative grid import in the figure) to the distribution substation bus during the day. The analysis shows that the grid imports start to decrease when the PV system starts injecting power to the bus. Since the system design is optimised for summer it can be seen that there is no net grid exports in summer. However, since load is low during winter, as shown in Fig. 12 the PV system exports excess power generated to adjacent distribution buses. Since power flows in the reverse direction in the network there is the possibility of voltage limit violation and increase in network losses.

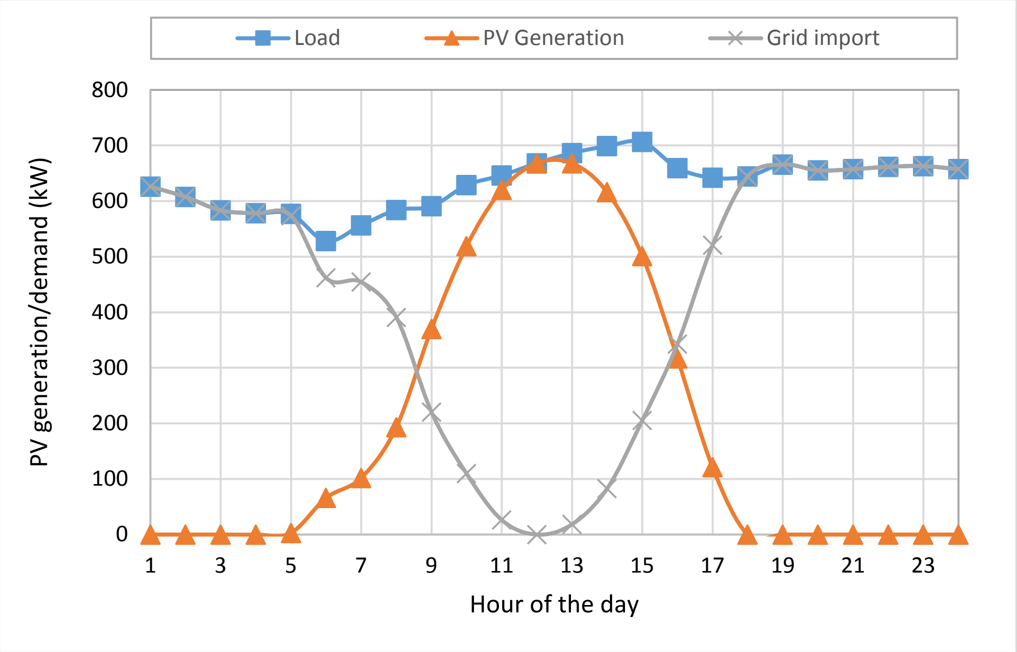

Fig. 11. Load and PV generation profiles for summer

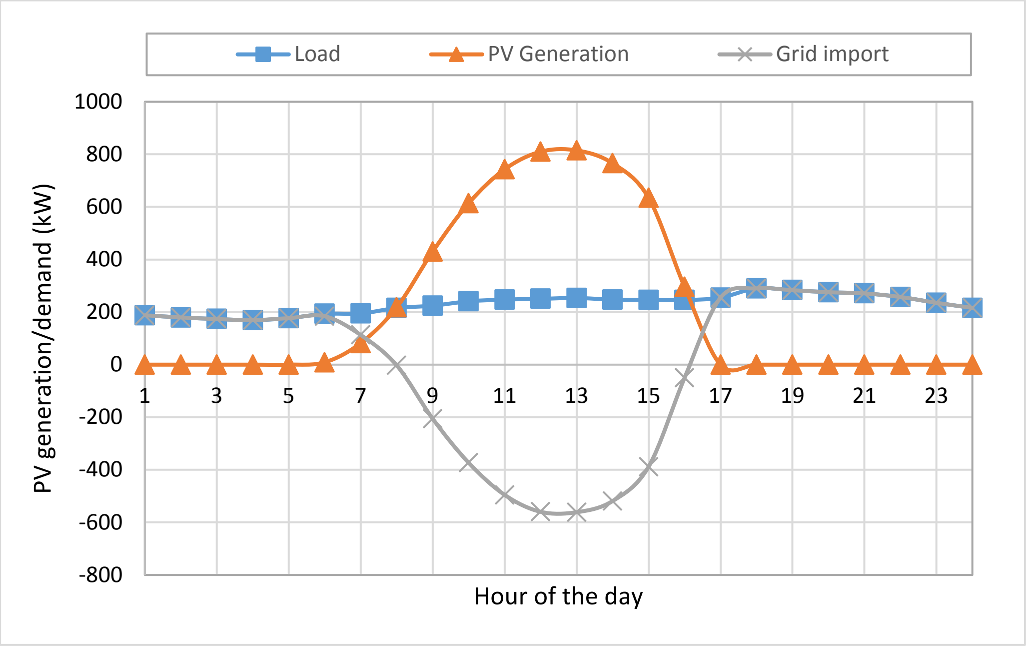

Fig. 12. Load and PV generation profiles for winter

3.3. Power flow and voltage profiles

The electrical power network of Bahrain as shown in Fig. 7 and 8 was modelled in PSSE software (V34.0.0). The point of integration of the 1MW PV system to the network is varied according the scenario considered (Table 2). A typical PV system is modelled in PSSE as a constant active power source (P) with no reactive power component (Q). As mentioned earlier in (section 2.4.1) there are two study cases for reach scenario; one for summer with high consumer electricity demand and the other for winter with low demand. For the summer case the peak PV generation and peak load coincides at 668kW. For winter, the PV system generation is 815kW while the typical load at the substation is 253kW. A constant power factor of 0.9 was used to for all loads. The total active and reactive loads for the network section considered are 21.376 MW and 10.912 MVAR for the summer case and 7.902 MW and 3.827 MVAR for the winter case.

The power flow study is conducted under normal operating conditions to determine the impact of connecting the 1MW PV system to the power network based on the scenarios mentioned in Table 2. Fig. 13 shows the total network active power losses for the all scenarios with summer load and PV conditions. The impact of the point of connection of the PV system to the network is clearly visible from Fig. 13. The losses for scenario 2 (PV connected to Bus 11) is higher than that for scenario 1 (base case without PV). The losses are the lowest for scenario 6 with PV at the far end of the distribution network (Bus 114). This highlights the need for Bahrain to have a utility policy that necessitates network connection location impact assessment for every largescale PV system.

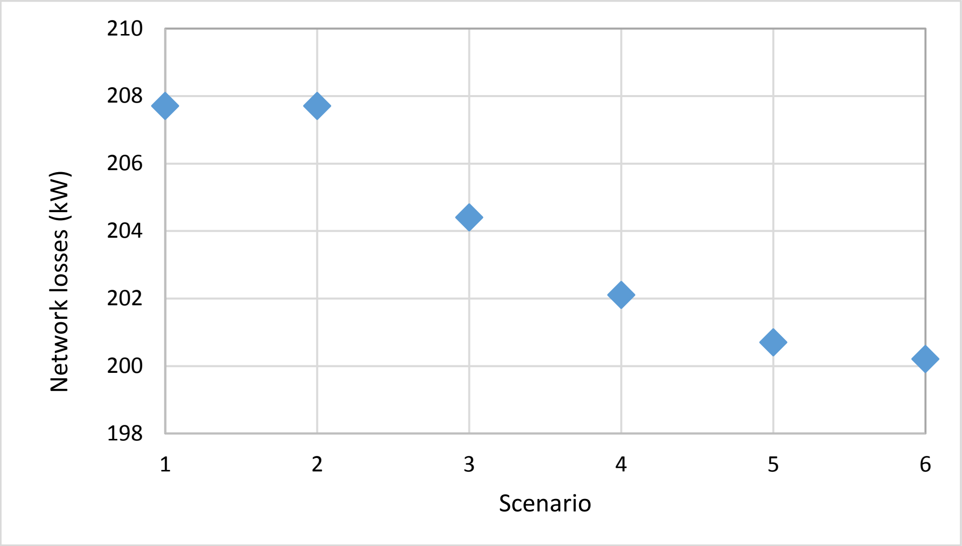

Fig. 13. Power losses at Primary substation during summer

Fig. 14 and 15 shows the voltages at the respective bus before and after connecting the PV system respectively for summer and winter. It is evident that effect on voltage is most significant for the integration of the PV system at the far end bus (i.e. Bus 114). If the voltage rises above 10% of the network nominal voltage i.e. above 1.1 p.u. it is a violation of the utility mandated limits. However, it can be observed that even for winter with a large grid export the proposed PV system does not violate the voltage limits. The highest voltage rise is about 1.033 p.u. which indicates that the network is capable of hosting PV systems bigger than 1MW.

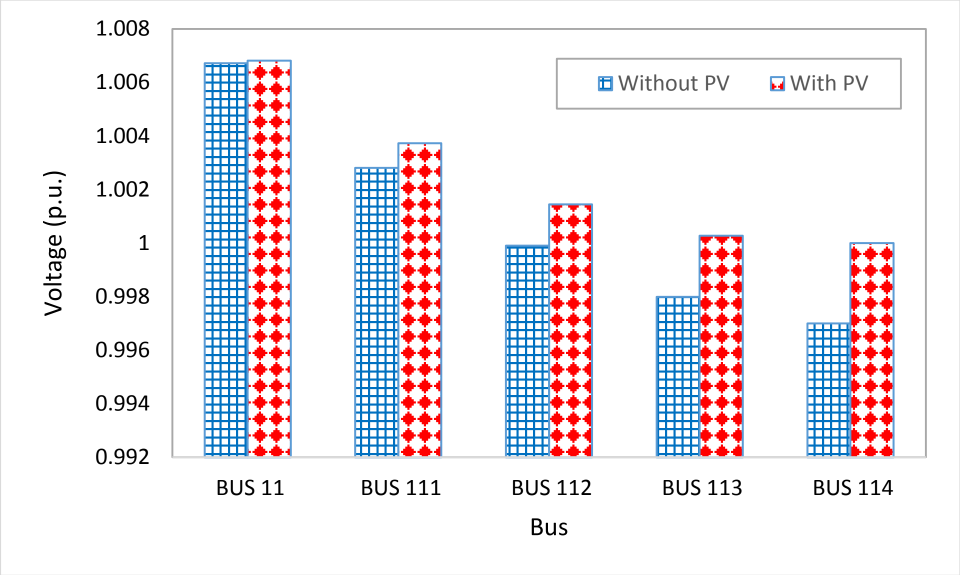

Fig. 14. Voltage at the point of PV connection during summer

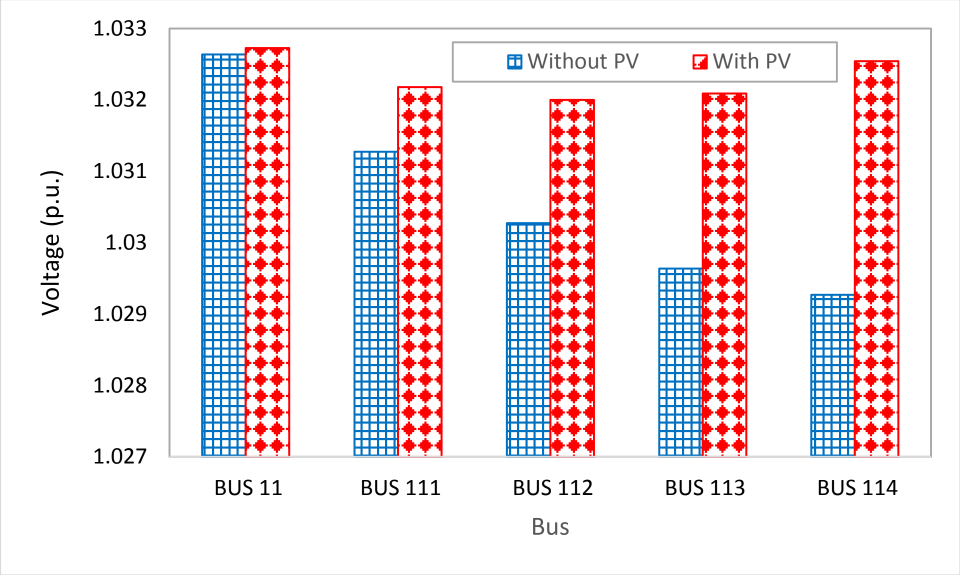

Fig. 15. Voltage at the point of PV connection during winter

Fig. 16 and 17 show the changes to the network voltage profile when PV is connected to different buses as described in the respective scenarios. The summer voltage profile is improved with PV integration to the network. However, for winter, due to reverse power flow there are differences. For scenario 2 i.e. with PV at bus 11, the voltages at buses 113 and 114 reduces slightly due to increased losses in the network. Voltage of bus 11 stays almost constant between scenarios. Except for bus 111, for which highest voltage condition occurs when PV is connected to that bus, a uniform highest voltage condition occurs with PV at bus 114. As in the case of any bus within a power network the absolute voltage magnitude between is function of the net loading at the buses and the network impedance. For the network operator having PV at bus 11 will be preferable as it can be easily disconnected for network maintenance. However due to the improvements in voltage profiles, it is recommended that PV be integrated to the far end bus 114.

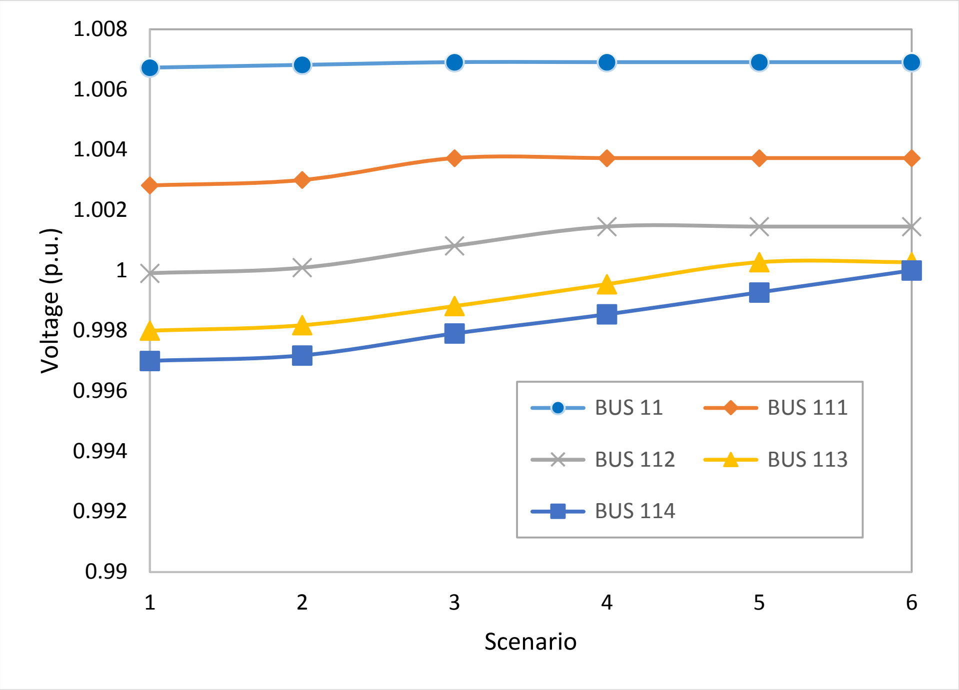

Fig. 16. Network voltage profile for the scenarios considered during summer

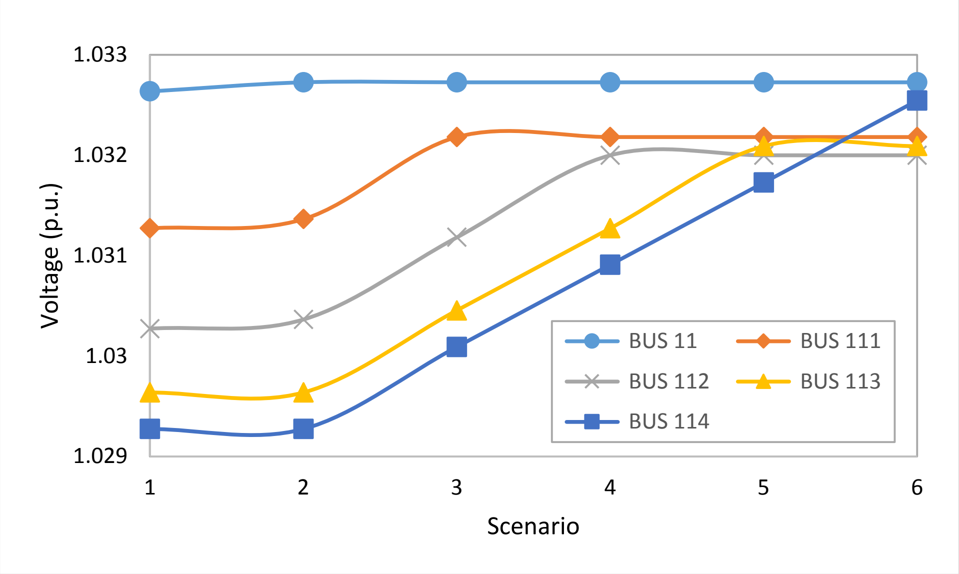

Fig. 17. Network voltage profile for the scenarios considered during winter

Since the PV is system connected a load bus, the results of power flow simulation show that the loading on the studied network decrease after the connection of the PV system. This decrease in net feeder loading will allow to connect more load in the same feeder. Therefore if load grows in the future PV systems can defer investments in network reinforcement (new cables, transmission lines etc.). Table 3 shows the power flow on the 11 kV network feeders for all scenarios in the summer case and Table 4 shows the same for winter. The impact of high summer loading is evident from Table 3. The high loading prevents reverse power flow due to PV generation. In case of winter, connecting a PV system to the any of the four distribution buses (as mentioned in the scenarios) will cover 80 % of the total load at the substation (not just the load at that bus). It is evident from Table 4 that reverse power flow occurs in winter. The maximum PV generation hosting capacity of the network will depend on the reverse power capacity of the 11 kV transformers and the automatic voltage regulators upstream in the network.

Table 3. Power flow in 11 kV feeders for the summer case

Scenario	**Feeder Loading (kVA)**							
	From	**To**	**From**	**To**	**From**	**To**	**From**	**To**
	11	**111**	**111**	**112**	**112**	**113**	**113**	**114**
1:PV Off	3000		2256		1506		750	
2:PV @ Bus 11	3000		2256		1506		750	
3:PV @ Bus 111	2442		2250		1500		750	
4:PV @ Bus 112	2436		1698		1500		750	
5:PV @ Bus 113	2436		1698		972		750	
6:PV @ Bus 114	2436		1698		972		360	

Table 4. Power flow in 11 kV feeders for the winter case

Scenario	**Feeder Loading (kVA)**							
	From	**To**	**From**	**To**	**From**	**To**	**From**	**To**
	11	**111**	**111**	**112**	**112**	**113**	**113**	**114**
1:PV Off	1068		798		534		264	
2:PV @ Bus 11	1068		798		534		264	
3:PV @ Bus 111	522		798		534		264	
4:PV @ Bus 112	522		384*		534		264	
5:PV @ Bus 113	522		384*		402*		264	
6:PV @ Bus 114	522		384*		402*		564*	

(* indicates that the active power flows in reverse direction)

3.4. Short circuit analysis

The Fault Analysis function of PSSE was used to conduct three phase short circuit analysis for all scenarios, for the network modelled in PSSE, in accordance with the IEC 60909 standard based on a three phase fault contribution of 15 kA from the main grid on the 11 kV bus of the distribution substation. Voltage used for the calculation was 1.1 p.u. The resulting of three phase fault currents at the 11 kV buses for all scenarios are shown in Table 5.

Table 5. Three phase short circuit currents

Scenario	**Fault current (kA) at the bus**				
	Bus 11	**Bus 111**	**Bus 112**	**Bus 113**	**Bus 114**
1:PV Off	15.000	12.208	10.004	8.364	7.140
2:PV @ Bus 11	15.047	12.238	10.023	8.377	7.149
3:PV @ Bus 111	15.047	12.254	10.035	8.386	7.156
4:PV @ Bus 112	15.047	12.254	10.047	8.396	7.164
5:PV @ Bus 113	15.047	12.254	10.047	8.406	7.172
6:PV @ Bus 114	15.047	12.254	10.047	8.406	7.180

The results shows that the three phase fault current contribution from the 1 MW PV system will be 47 A on the 11 kV primary substation bus. This value is very small (less than 0.4%) compared to the main grids contribution on the 11kV system which is 15 kA. Hence it can be concluded that the integration of the 1 MW system does not affect the security of the system.

4. Conclusions and policy implications

In this work an assessment of the potential technical impacts of integrating a utility-size (1MW) photovoltaic system optimized for peak load matching to the electrical power network of Bahrain was carried out. A systematic modelling approach was followed using PVGIS for solar resource analysis and location selection; PVsyst for simulating PV system operation, and PSSE to model and analyse the electrical power distribution system. The following recommendations are based on the results of the analysis:

1. Given Bahrain’s summer electricity demand being higher than the winter demand due to air conditioning loads, utility policies should promote largescale PV system designs optimised for summer peak load to reduce wastage of potential energy yield.
2. As there is a reduction in PV system PR in summer, utilities should consider the economic feasibility of forced cooling of largescale PV plants during summer to avoid wastage of useful energy.
3. The power losses in the network was found to be impacted by the location of connection of PV. Utility policies should necessitates impact assessment of network connection location for every largescale PV system installation.
4. Under the present network configuration the integration of largescale PV systems lead to a decrease in net feeder loading which allows the connection of more load the same feeder. Therefore, if load grows in the future, PV systems can defer investments in network reinforcement (new cables, transmission lines etc.).

From the analysis it is clear that with the present load profiles and network configuration, the power network of Bahrain is capable of hosting largescale PV systems without the need for reinforcements. Given the lowering cost of PV technologies, the high solar resource availability and potential to match Bahrain load profiles, it is safe to say that PV holds a bright future in Bahrain.

Future work will look into financial cost and benefit aspects of large scale network integrated PV in Bahrain.

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References

Abdullah, A., Ghoneim, A., Al-Hasan, A., 2002. Assesment of grid-connected photovoltaic systems in the Kuwaiti climate. Renewable Energy 26(2), 189-199. http://dx.doi.org/10.1016/s0960-1481(01)00115-x.

Almasoud, A. Gandayh, H., 2015. Future of solar energy in Saudi Arabia. Journal Of King Saud University - Engineering Sciences 27(2), 153-157. http://dx.doi.org/10.1016/j.jksues.2014.03.007.

Alnaser, N., 2015. Building integrated renewable energy to achieve zero emission in Bahrain. Energy and Buildings 93, 32-39. http://dx.doi.org/10.1016/j.enbuild.2015.01.022

Alnaser, W., Al-Karaghouli, A., 2000. Wind availability and its power utility for electricity production in Bahrain. Renewable Energy 21(2), 247-254. http://dx.doi.org/10.1016/s0960-1481(00)00072-0.

Alnaser, W., Alnaser, N., 2011. The status of renewable energy in the GCC countries. Renewable And Sustainable Energy Reviews 15(6), 3074-3098. http://dx.doi.org/10.1016/j.rser.2011.03.021.

Alnatheer, O., 2006. Environmental benefits of energy efficiency and renewable energy in Saudi Arabia's electric sector. Energy Policy 34(1), 2-10. http://dx.doi.org/10.1016/j.enpol.2003.12.004.

Alnatheer, O., 2005. The potential contribution of renewable energy to electricity supply in Saudi Arabia. Energy Policy 33(18), 2298-2312. http://dx.doi.org/10.1016/j.enpol.2003.12.013.

Al-Sabounchi, A., Al-Hammadi, E., Yalyali, S., Al-Thani, H., 2013. Photovoltaic-grid connection in the UAE: Technical perspective. Renewable Energy 49, 39-43. http://dx.doi.org/10.1016/j.renene.2012.01.070.

Al-Sabounchi, A., Yalyali, S., Al-Thani, H., 2013. Design and performance evaluation of a photovoltaic grid-connected system in hot weather conditions. Renewable Energy 53, 71-78. http://dx.doi.org/10.1016/j.renene.2012.10.039.

Alyahya, S., Irfan, M., 2016. Role of Saudi universities in achieving the solar potential 2030 target. Energy Policy 91, 325-328. http://dx.doi.org/10.1016/j.enpol.2016.01.019.

Barker, P.P. and De Mello, R.W., 2000. Determining the impact of distributed generation on power systems. I. Radial distribution systems. IEEE Power Engineering Society Summer Meeting, 1645-1656. http://dx.doi.org/10.1109/PESS.2000.868775

Bhutto, A., Bazmi, A., Zahedi, G., Klemeš, J., 2014. A review of progress in renewable energy implementation in the Gulf Cooperation Council countries. Journal Of Cleaner Production 71, 168-180. http://dx.doi.org/10.1016/j.jclepro.2013.12.073.

Bouhouras, A., Marinopoulos, A., Labridis, D., Dokopoulos, P., 2010. Installation of PV systems in Greece—Reliability improvement in the transmission and distribution system. Electric Power Systems Research 80(5), 547-555. http://dx.doi.org/10.1016/j.epsr.2009.10.018.

Chrosis Sustainable Solutions, 2012. Whitepaper on PR vs. CUF. http://chrosis.de/wp-content/uploads/2012/12/PR-vs-CUF-WP.pdf. (accessed 2.05.16).

Ciulla, G., Brano, V.L., Di Dio, V. and Cipriani, G., 2014. A comparison of different one-diode models for the representation of I–V characteristic of a PV cell. Renewable and Sustainable Energy Reviews, 32, pp.684-696. http://dx.doi.org/10.1016/j.rser.2014.01.027

Djurdjevic, D., 2011. Perspectives and assessments of solar PV power engineering in the Republic of Serbia. Renewable And Sustainable Energy Reviews 15(5), 2431-2446. http://dx.doi.org/10.1016/j.rser.2011.02.025.

El-Sebaii, A., Al-Ghamdi, A., Al-Hazmi, F., & Faidah, A., 2009. Estimation of global solar radiation on horizontal surfaces in Jeddah, Saudi Arabia. Energy Policy 37(9), 3645-3649. http://dx.doi.org/10.1016/j.enpol.2009.04.038.

Eltawil, M., Zhao, Z., 2010. Grid-connected photovoltaic power systems: Technical and potential problems—A review. Renewable And Sustainable Energy Reviews 14(1), 112-129. http://dx.doi.org/10.1016/j.rser.2009.07.015.

Energy.sourceguides.com, 2017. Photovoltaic Module Manufacturers in the United Arab Emirates. http://energy.sourceguides.com/businesses/byP/solar/pvM/byB/manufacturers/byGeo/byC/UAE/UAE.shtml (accessed 7.01.17).

ESB International, 2010. Planning Approach for urban distribution network in Bahrain. http://www.esbi.ie/news/pdf/ESBI-White-Paper-Planning-Urban-Distribution-Networks-Bahrain.pdf. (accessed 15.05.16).

EWA (Bahrain Electricity and Water Authority), 2015. System Generation Availability and Peak Load for 2015. http://mew.gov.bh/default.asp?action=category&id=64. (accessed 10.05.16).

Griffiths, S., Mills, R., 2016. Potential of rooftop solar photovoltaics in the energy system evolution of the United Arab Emirates. Energy Strategy Reviews 9, 1-7. http://dx.doi.org/10.1016/j.esr.2015.11.001.

Grossmann, W., Grossmann, I., Steininger, K., 2013. Distributed solar electricity generation across large geographic areas, Part I: A method to optimize site selection, generation and storage. Renewable And Sustainable Energy Reviews 25, 831-843. http://dx.doi.org/10.1016/j.rser.2012.08.018.

Gómez, M., López, A., Jurado, F., 2010. Optimal placement and sizing from standpoint of the investor of Photovoltaics Grid-Connected Systems using Binary Particle Swarm Optimization. Applied Energy 87(6), 1911-1918. http://dx.doi.org/10.1016/j.apenergy.2009.12.021.

Harder, E., Gibson, J., 2011. The costs and benefits of large-scale solar photovoltaic power production in Abu Dhabi, United Arab Emirates. Renewable Energy 36(2), 789-796. http://dx.doi.org/10.1016/j.renene.2010.08.006.

Information & eGoverment Authority, 2015. Bahrain Open Data Portal. http://www.data.gov.bh/en/ResourceCenter. (accessed 3.06.16).

IRENA, 2016. Renewable energy market analysis-The GCC region. http://www.irena.org/DocumentDownloads/Publications/IRENA_Market_GCC_2016.pdf. (accessed 20.05.16).

Joint Research Centre. Photovoltaic Geographical Information System. http://re.jrc.ec.europa.eu/pvgis/. (accessed 1.05.16).

Karki, P., Adhikary, B., Sherpa, K.,2012. Comparative study of grid-tied photovoltaic (PV) system in Kathmandu and Berlin using PVsyst. 2012 IEEE Third International Conference On Sustainable Energy Technologies (ICSET). http://dx.doi.org/10.1109/icset.2012.6357397.

Li, D., Cheung, K., Lam, T., Chan, W., 2012. A study of grid-connected photovoltaic (PV) system in Hong Kong. Applied Energy 90(1), 122-127. http://dx.doi.org/10.1016/j.apenergy.2011.01.054.

Mansouri, N., Crookes, R., Korakianitis, T., 2013. A projection of energy consumption and carbon dioxide emissions in the electricity sector for Saudi Arabia: The case for carbon capture and storage and solar photovoltaics. Energy Policy 63, 681-695. http://dx.doi.org/10.1016/j.enpol.2013.06.087.

Mezher, T., Dawelbait, G., Abbas, Z., 2012. Renewable energy policy options for Abu Dhabi: Drivers and barriers. Energy Policy 42, 315-328. http://dx.doi.org/10.1016/j.enpol.2011.11.089.

Mohamad, A., Hashim, N., Hamzah, N., Nik Ismail, N., & Abdul Latip, M. (2011). Transient stability analysis on Sarawak's Grid using Power System Simulator for Engineering (PSS/E). 2011 IEEE Symposium On Industrial Electronics And Applications. http://dx.doi.org/10.1109/isiea.2011.6108766.

Mokri, A., Aal Ali, M., Emziane, M., 2013. Solar energy in the United Arab Emirates: A review. Renewable And Sustainable Energy Reviews 28, 340-375. http://dx.doi.org/10.1016/j.rser.2013.07.038.

Radhi, H., 2011. On the value of decentralised PV systems for the GCC residential sector. Energy Policy 39(4), 2020-2027. http://dx.doi.org/10.1016/j.enpol.2011.01.038.

Ramadhan, M., Naseeb, A., 2011. The cost benefit analysis of implementing photovoltaic solar system in the state of Kuwait. Renewable Energy 36(4), 1272-1276. http://dx.doi.org/10.1016/j.renene.2010.10.004.

Ramli, M., Hiendro, A., Sedraoui, K., Twaha, S., 2015. Optimal sizing of grid-connected photovoltaic energy system in Saudi Arabia. Renewable Energy 75, 489-495. http://dx.doi.org/10.1016/j.renene.2014.10.028.

Rehman, S., El-Amin, I., 2012. Performance evaluation of an off-grid photovoltaic system in Saudi Arabia. Energy 46(1), 451-458. http://dx.doi.org/10.1016/j.energy.2012.08.004.

Reiche, D., 2010. Energy Policies of Gulf Cooperation Council (GCC) countries—possibilities and limitations of ecological modernization in rentier states. Energy Policy 38(5), 2395-2403. http://dx.doi.org/10.1016/j.enpol.2009.12.031.

Sharples, S., Radhi, H., 2013. Assessing the technical and economic performance of building integrated photovoltaics and their value to the GCC society. Renewable Energy 55, 150-159. http://dx.doi.org/10.1016/j.renene.2012.11.034.

Singh, G., 2013. Solar power generation by PV (photovoltaic) technology: A review. Energy 53, 1-13. http://dx.doi.org/10.1016/j.energy.2013.02.057.

Sharma, V., Chandel, S., 2013. Performance analysis of a 190 kWp grid interactive solar photovoltaic power plant in India. Energy 55, 476-485. http://dx.doi.org/10.1016/j.energy.2013.03.075.

PVsyst., 2014. Pvsyst user's manual http://www.pvsyst.com/images/pdf/PVsyst_Tutorials.pdf. (accessed 7.05.16).

Appendix

Table A1. Electrical Specification of a typical Dusol PV module used (at STC)

Parameter	Value
Nominal power (P_{max})	290 W_P
Open-circuit voltage (V_{OC})	45 V
Short circuit current (I_{SC})	8.57 A
Voltage at maximum power (V_{mpp})	36.3 V
Maximum power current (I_{mpp})	8.00 A
Voltage coefficient of temperature of solar module	(-0.329)%/°C

Table A2. Technical data of the inverter (SMA Sunny Central 200):

	Parameter	*Value*
Input Specifications	Nominal power DC (P_{PV})	210 kW
	DC voltage range (U_{DC})	450 V – 820 V
	Maximum permissible DC voltage (U_{DC})	880 V
	Maximum permissible DC current (I_{DC})	472 A
Output Values	Nominal AC output power (P_{AC})	200 kW
	Operating grid voltage +/- 10 % (U_{AC})	400 V
	Nominal AC current ($I_{AC,Nom}$)	289 A
	Power factor	>0.98