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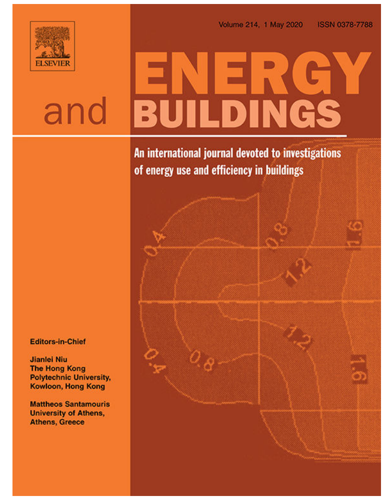

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A.A. EzzEldin, N.W. Alnaser, R. Flanagan, W.E. Alnaser

PII: S0378-7788(22)00660-0
DOI: https://doi.org/10.1016/j.enbuild.2022.112489
Reference: ENB 112489

To appear in: *Energy & Buildings*

Received Date: 15 August 2022
Revised Date: 4 September 2022
Accepted Date: 14 September 2022

Please cite this article as: A.A. EzzEldin, N.W. Alnaser, R. Flanagan, W.E. Alnaser, The Feasibility of Using Rooftop Solar PV Fed to the Grid for Khalifa Town Houses in the Kingdom of Bahrain, *Energy & Buildings* (2022), doi: https://doi.org/10.1016/j.enbuild.2022.112489

The Feasibility of Using Rooftop Solar PV Fed to the Grid for Khalifa Town Houses in the Kingdom of Bahrain

A. A. EzzEldin[1], N. W. Alnaser[2] , R. Flanagan[3], W. E. Alnaser[4]
[1]Department of Architectural Engineering, Kingdom University, Kingdom of Bahrain
E - mail : amani.ezzeldin@gmail.com
[2]Department of Architecture and Interior Design, College of Engineering, University of Bahrain, Isa Town, Kingdom of Bahrain. E - mail: nalnaser@uob.edu.bh
[3] School of Construction Management and Engineering, University of Reading, Reading, UK
E- mail : r.flanagan@reading.ac.uk
[4]Department of Natural Resources and Environment, College of Graduate Studies, Arabian Gulf University, Manama, Kingdom of Bahrain
E-mail: walanser@agu.edu.bh

Corresponding Author: W.E.Alnaser, Arabian Gulf University ,P.o.Box 26671, Manama , Kingdom of Bahrain, E mail. walnaser@agu.edu.bh

Abstract

The fast-growing construction industry and residential buildings in Bahrain create massive energy and environmental demands. Therefore, Bahrain has set a national renewable energy target of 5% by 2025.

The novelty of this study is investigating the feasibility of using rooftop photovoltaic systems, Fed to the national grid, in residential buildings (Khalifa Town, Bahrain) - located in arid zone - combining architecture aesthetics, social acceptability and functionality. The assessment of the rooftop area and the PV system modeling was carried using AutoCAD and PVsyst software. Consideration was given to design aesthetics and the functionality of having PV panels on the roof, without losing the use of the roof for social gathering and activities. Our results show that installing 17 kW - PV panels, for each of 1,724 villas in the town, will produce annual solar electricity of 44,953 MWh, which is sufficient to meet about 43% of the total town's electricity needs. This rooftops installation will cut CO_2 emission by 34,794 tons, i.e., reducing 21% of the town's total CO_2 emissions.

The study shows that the payback will be 9.6 years if the government purchases each kWh of solar electricity for 29 fils (USD ¢7.5). Establishing feed-in-tariff policy (FIT)will reduce the payback period and accordingly boost local PV manufacturing and create more green - collar jobs.

Keywords: Rooftop PV, residential PV generation, CO_2 emission, Feed-in-tariff, Bahrain

Introduction

The world has been experiencing huge changes over the last century that have led to significant environmental and energy challenges. These changes were mainly due to the rapid economic development and significant population growth which have risen dramatically from below a billion a century ago to over 7 billion today [1]. Above all of these challenges comes the issue of climate change, carbon reduction, and increased energy demands especially in the Arab region where 5.1% of the world's total primary energy supply and 7.8% of its carbon dioxide emissions has been accounted, much of it is generated in the GCC countries [2]. The Gulf Cooperation Council (GCC) nations (Saudi Arabia, Bahrain, Kuwait, Oman, United Arab Emirates and Qatar) confront the problem of growing energy demands owing to different aspects like developing population, escalating rates of urbanization, rapid economic and industrial development, and increasing living standards [3]. According to International Energy Outlook [4]. energy consumption in non-OECD countries (among them the GCC countries) rises 41% between 2015 and 2040 compared to a 9% increase in OECD countries.

The average energy consumption per capita in GCC countries is over seven times higher than the worldwide average [5]. Statistics indicate that the building sector accounts for around 80% of the total electricity consumption, especially residential buildings. For example, in Bahrain and Saudi Arabia, over 50% of the total electricity produced in the country is used in the residential sector [6]. The excessive consumption of fossil fuels and electricity gets converted into greater amounts of environmental emissions with the GCC countries amongst the highest CO_2 emissions per capita [7]. However, recent trends in the GCC region show that there is a substantial degree of comprehension to shift towards renewable energy and sustainability, especially in the construction sector.

Over the last decade the GCC countries have been endorsing countless aspects of sustainable urban development and energy efficiency through policies and legislative instruments. This has encouraged the rapid application of different sustainable technologies and renewable energy to overcome the environmental challenges. Solar energy and wind power have always been the prominent sources of clean energy. Renewable energy is attractive; despite supply chain disruptions, shipping delays, and surging prices for wind and solar energy components, capacity additions grew 17% in 2021 to reach a new high of more than 314 GW of added capacity - grew 11% to reach around 3,146 GW. The solar PV added 175 GW in 2021 to reach a cumulative total of around 942 GW [8]. The geographical location of GCC countries, means they are well fitted to receive an abundant amount of solar energy (nearly 500-600 W/m^2), equivalent to 1.5 million barrels of crude oil [9], which gives tremendous potential for solar electricity generation. The GCC region has one of the world's highest solar capacities, considering the geographic, environmental, and economic characteristics of this region. The average Global Solar Radiation (GSR) available to photovoltaics cells in the area is calculated to be approximately 6 kWh/m^2/day [10] while the Direct Normal Irradiance figures available for solar concentrating technologies are approximately 4.5KWh/m^2/day. In 2017, the total annual electricity generated in the region increased to 680 TWh, and in 2018, it increased to 691.5 TWh, corresponding to an increase of greater than 11 GWh within 1 year (Fig. 1) [11] . The total annual consumption in GCC was recorded as 559.3 TWh, which increased to 573.11 TWh in 2018, corresponding to an increase of 13.8 TWh within 1 year [11] .

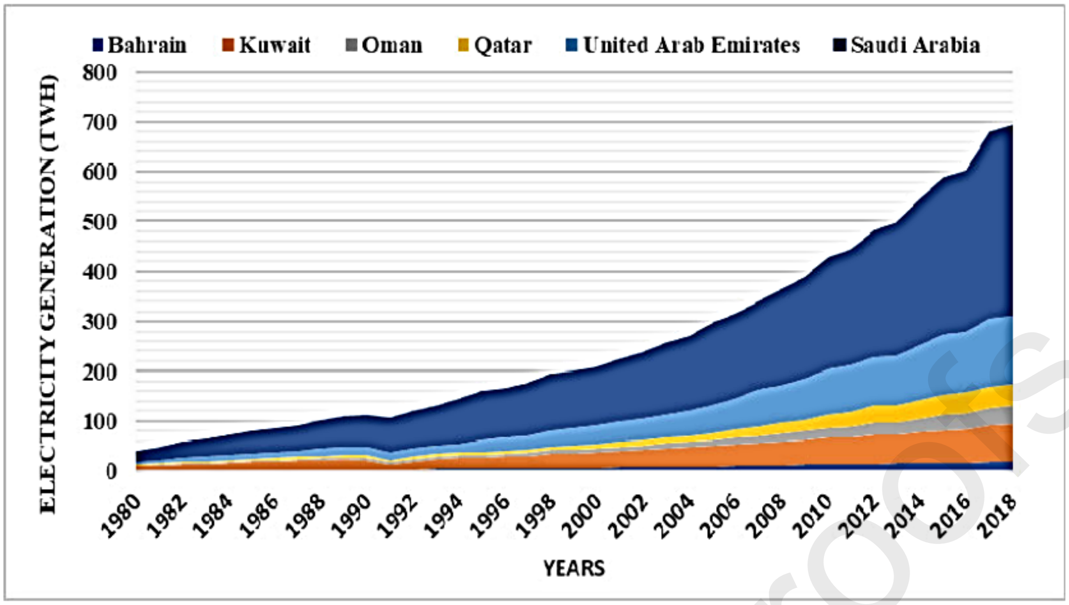


Fig. 1: Electricity generation in the GCC region [11].

A study affirmed that the majority of Bahraini buildings lack sustainability measures being built with insufficient environmental considerations, which generates a huge energy crisis as it consumes around 80% of the total electricity consumption [6].

Limited studies and research have addressed the issue of deployment of PV systems in Bahrain's building sector. The assessment of PV application on building rooftops in Bahrain, especially in residential buildings, is an important consideration for policy makers, government, and users. Therefore, this research targeted this information gap.

Installing PV panels on residential building rooftop areas is an important concern since it works in parallel with the sustainable energy transition anticipated in the Economic Vision 2030 of Kingdom of Bahrain. Bahrain needs to utilize the high solar potential in the country, but the land limitation and the cost is a barrier. It makes no sense to use land that costs BD 100 (USD 260) per ft^2 (or BD 300 = USD 780) per m^2) to install a PV system that will provide daily solar electricity of 28 kWh per day (annually 10,220 kWh, which is worth BD 30 (USD 78) – if the unit price is 3 fils (USD¢0.75) per kWh – and BD 300 – if unit price is 30 fils (USD¢7.8) per kWh). Using the rooftops of buildings offers a feasible solution, where Bahrain's total land area is only 780 km^2.

In Oman, researchers reported a method for optimal sizing of a standalone PV system for remote areas in Sohar. The implantation of MATLAB , hourly meteorological data and load demand had revealed that the tilt angle of a PV array must be adjusted twice a year; slanted at 49° in the period of 21/09 to 21/03, while it must be horizontal (tilt angle is zero) in the period of 21/03 to 21/09 , where the gained solar electricity will increase by 20.6% [12]. On another paper a design and evaluation practice of a grid-connected photovoltaic system installed in Sohar, Oman, was reported. The capacity, specific yield and performance factors were used to evaluate the performance. The cost of energy and payback period were also evaluated [13]. Their results show that the capacity and the yield factors for the proposed system are 21% and 1875 kWh/kW/year respectively while the performance factor of the system was 84.6%. The cost of the energy generated and the payback period of the proposed system were 0.045 USD/kWh and 11 years, respectively [13].

This study will be the first of its kind to actually examine the power generation potential of PV system on the rooftop of residential buildings in Khalifa Town in Bahrain (classified as smart city) from an economic and environmental perspective. It will help in developing awareness of the positive impact of PV applications over the long-term to encourage Bahraini authorities to be involved with new policies in delivering more sustainable residential building projects.

Herein studying the potential of making use of the rooftop of the houses in Khalifa Town, that is located in an arid zone, without spoiling the architecture aesthetics, social acceptability and functionality. A 17 kW -PV panels will be installed at rooftop of each villa and the generated solar electricity will be fed to the national grid. The study covers a descriptive economic and environmental assessment of using a PV system taking into consideration the consideration the followings:

- The net utilizable rooftop area for PV application on residential buildings.
- The most appropriate layout of the roof that maximize PV utilization and withstanding other structural and mechanical features.
- The economic impact in using tilted PV panels on the roofs at angle less than the latitude of Bahrain (26° N) to overcome the wind stress on the PV panels that may destroy the PV system and also not to spoil the beauty of sight of the buildings.
- The size CO_2 bating in using roof top PV installation.

This study provides valuable data and analysis for the government of Bahrain, investors and developers interested in photovoltaic system in Bahrain and nearby desertic zones.

Methodology

The Southern New Town, so- called Khalifa Town, (Fig.2) has been selected to be a study area for an initiative by the Government of Bahrain and a blueprint in developing a modern planning, urban design and architectural Innovations. It utilizes clean energy such as solar energy, including walking neighborhoods style considering Bahrain's heritage and contemporary comfort.

The town is suitable for the study due its large size, it is expected to deliver over 4,600 new villas and flats. Therefore, it is an opportunity to investigate the use of the building rooftops of various sizes, to install PV panels to provide power for part of the house. This is an important investigation since electricity consumption in Bahrain has increased drastically to reach 29.21 TWh in 2018 [14] as shown in Fig.3

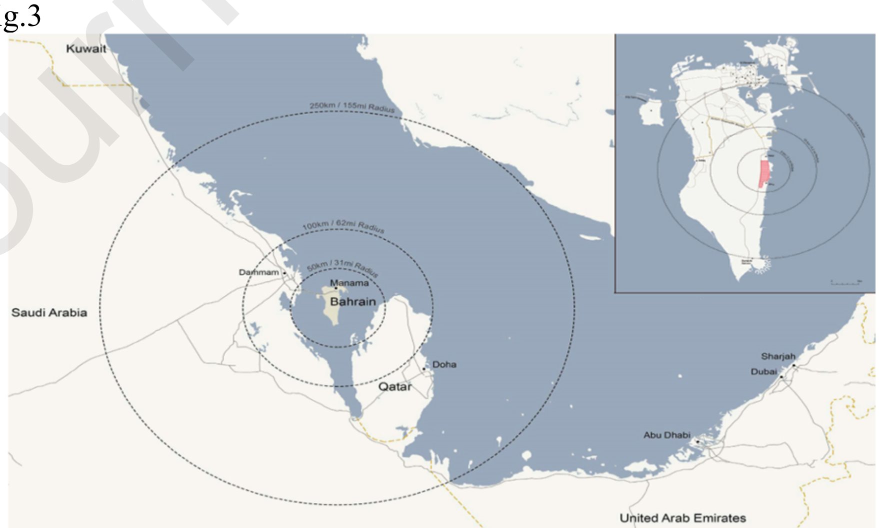
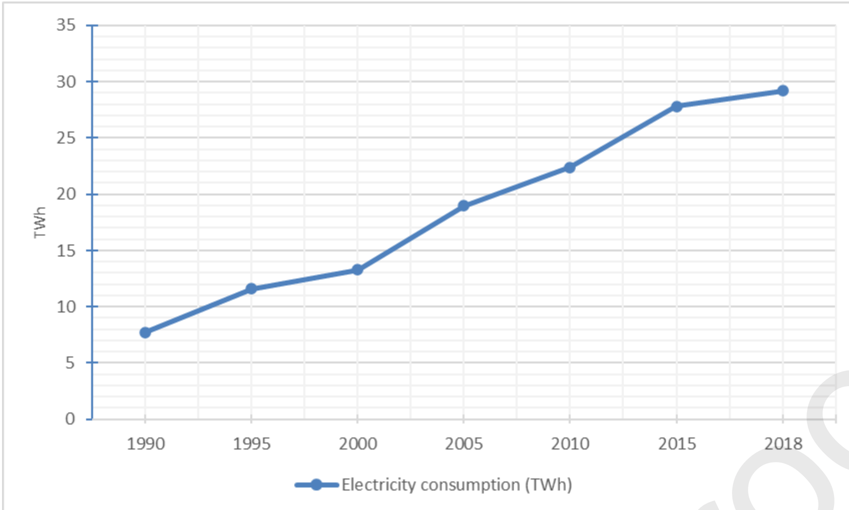


Fig. 2 : The location of Khalifa , Kingdom of Bahrain [15] .

Fig.3: Electricity consumption in Bahrain 1990-2018 [14].



Aiming to meet Bahrain's growing housing demand, Phase One of the project was designed to include 1,700 units along with various public facilities. Thus, 120 units were constructed first as a prototype to investigate its functionality as shown in Fig. 4 [15]. These units consist of five villa types (A1, A2, B1, B2 & C2) with approximate roof area of 100 m^2 per villa.

The design of the villas was inspired by the Bahraini traditional culture. Therefore, the various house spaces were articulated to respect the strong family ties. The roof was designed to be treated as a green roof having a small pergola to provide shade for the residents to communicate. However, it needs to be modified to embrace both tradition and sustainability.

Fig. 5 explains the structure of examining the 120 houses' rooftop spaces for the PV installation through different activities, which include solar resource assessment, rooftop area valuation, PV calculation, and system modeling, along with economic and environmental assessment.

The typical nature of building roofs of these villas is flat with high parapet walls, this will require some minor alteration in the roof area to consider the tilt angle and the orientation of the panel to maximize the solar electricity yield. This includes elevating the panels on pillars facing the south orientation which will serve as both an insulation and shading element as well as a power generation tool.

The main aim of this study is to explore the viability for producing energy through the PV systems on residential rooftops in Bahrain, it is important to employ an accurate tool for obtaining realistic data. Based on the relevant literature [6,14,15], calculations are carried out on the system design by using a software tool, known as PVsyst, which is one of the effective solar industry's energy modeling methods for simulating the energy harvest of a future project site. The software includes customizable solar module parameters, which allows studying size, design, and analyze data of complete PV systems. PVsyst has an extensive meteorological database for several locations around the globe. It also allows manual insertion of calculated data for locations not included in the app. The findings are presented in the form of a complete report with charts and tables.

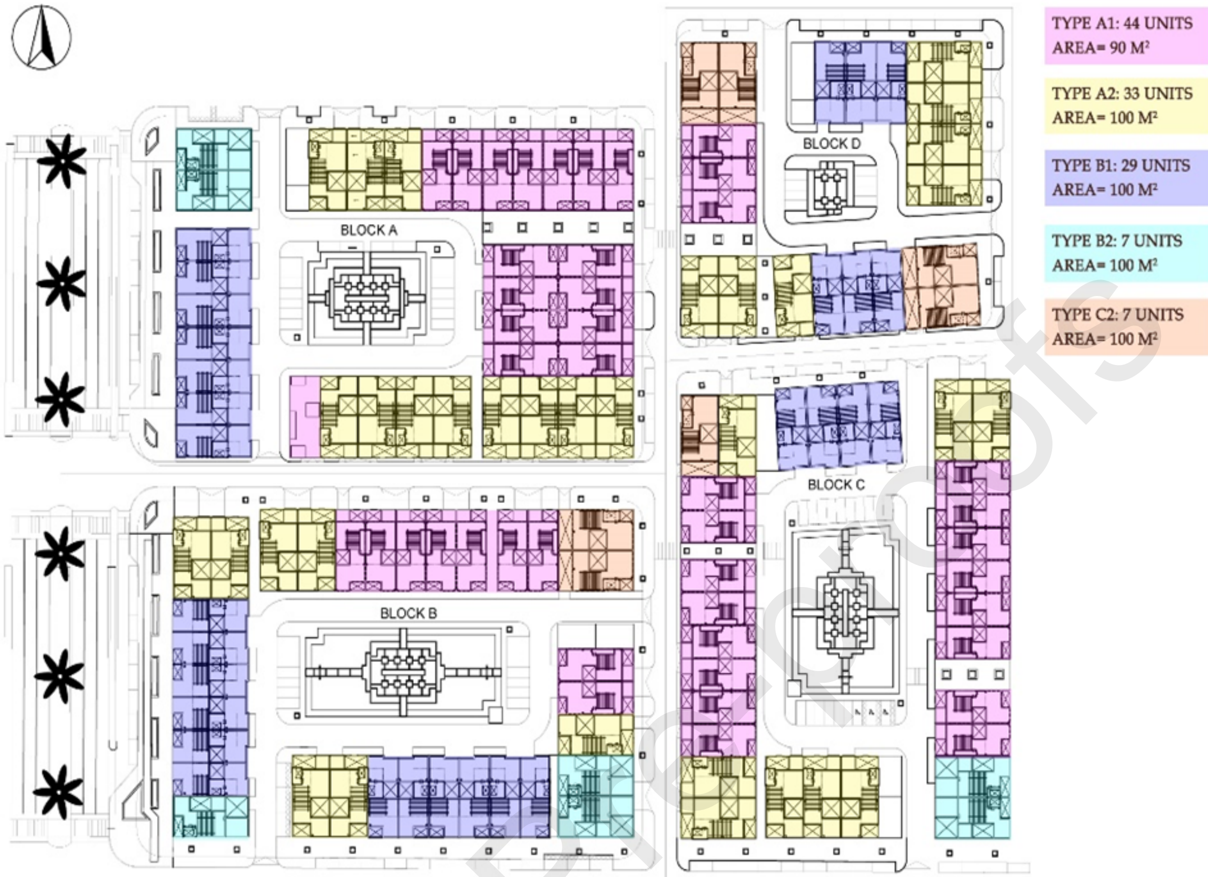


Fig. 4: Khalifa Town master plan with houses classification [15].

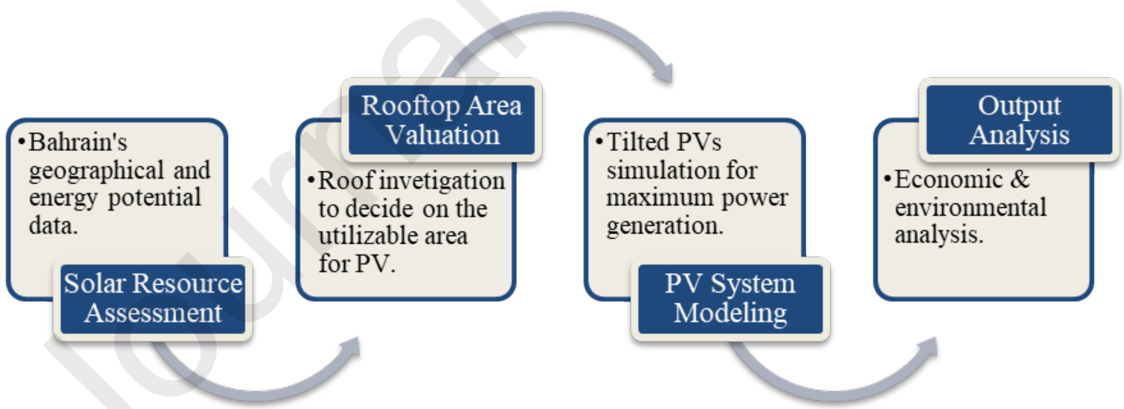


Fig.5 : Methodology of the study.

The findings form the program are obtained through four main stages. The first stage requires defining the project in terms of geographical location and meteorological data. The second section is defining the various parameters like orientation, tilt angle, and shading. The third stage is choosing the PV module type along with various system information needed for the design, like the power load and inverters. The fourth stage involves the simulation of the input information, the outputs are summarized charts and tables.

The study area consists of 120 villas of five types (A1, A2, B1, B2 & C2) with an approximate roof area of 100 m^2 per villa. The rooftop area analysis shows the total net available roof area on all houses is 11,560 m^2. However, building rooftops in Bahrain are usually characterized by being dominated by a variety of architectural and structural features, facilities that restrict the amount of space available for PV applications, especially those elements that impose substantial shading effect constraint like the high parapet walls and the staircase room.

Result and discussion

According to the Sustainable Energy Unit in Bahrain, the country targets to develop 5% of renewable energy projects by 2025 and 10% by 2035 [16]. The Ministry of Electricity and Water established a net-metering policy to allow users to produce grid-connected electricity from renewable sources for self-utilization and feed over generation to the national network (EWA Resolution NO. 2, 2017).

Khalifa Town is a new town situated in the Southern Province of Bahrain. According to the software estimates, it has an annual solar radiation level of about 2,016.1 kWh/m^2. Table 1 shows the monthly distribution of solar radiation which is very important to determine the solar electricity production, as well as other metrological parameters that affect the performance, availability and ageing of a PV system. These figures are based on high- resolution solar and meteorological database developed and operated by Solargis [15].

The scope of PV applications on rooftops were investigated where one of the key design considerations is to calculate the available roof space. Areas of the five villas rooftops were calculated using AutoCAD software and presented in Table 2.

Like all building rooftops in Bahrain, the structure of building roofs is usually occupied with broad architectural and structural features and facilities that limit both the availability and shading of space in terms of PV applications. Fig.6 illustrates the major obstacles that imposed an impact on the roof's viability for PV applications like staircase room, high balustrade walls, HVAC (Heating, ventilation, and air conditioning) system units, satellite antennas, and water heater and tanks.

It is important not to reduce the valued time families might have together by using the roof, especially when Bahrain weather is 70% moderate throughout the year. From an aesthetic point of view, the overall look of the house is an important factor to be taken into consideration in this study. Investigations were undertaken to find an optimum solution to balance between energy production and the architectural presentation of the system. As a result, the study considered using an elevated PV panel on a 3m high metal structure. This configuration has many advantages as it helps to maximize the space available for PVs, insulate the rooftop floor from direct sun radiation, thus reducing the cooling and heating load. Having a shaded roof is a facility that the resident usually looks for.

Table 1: The Annual Global Horizontal Irradiation (GHI) , Direct Normal Irradiation (DNI), Diffused Horizontal Irradiation (DIF) and Temperature at Khalifa Town, South of the Kingdom of Bahrain [15].

Month	GHI (kWh/m^2)	DNI (kWh/m^2)	DIF (kWh/m^2)	TEMP (°C)
January	113.0	108.6	55.3	17.1
February	123.2	104.4	60.5	17.8
March	163.0	119.2	80.2	20.5
April	177.5	113.1	92.0	24.4
May	215.7	146.3	101.7	28.9
June	224.4	165.9	97.4	31.9
July	218.2	142.8	106.4	33.3
August	209.0	145.4	98.1	33.8
September	186.9	147.9	81.3	32.5
October	161.2	141.6	72.2	29.5
November	116.7	107.6	57.4	24.4
December	107.3	106.7	53.4	19.4
Annual	**2016.1**	**1549.6**	**955.8**	**26.1**

Table 2: Areas of the rooftops of the five villa types at Khalifa Town, Kingdom of Bahrain.

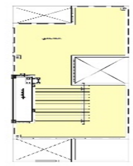
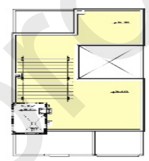
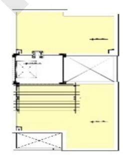
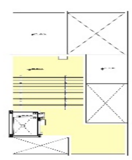
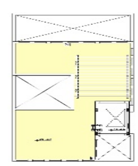
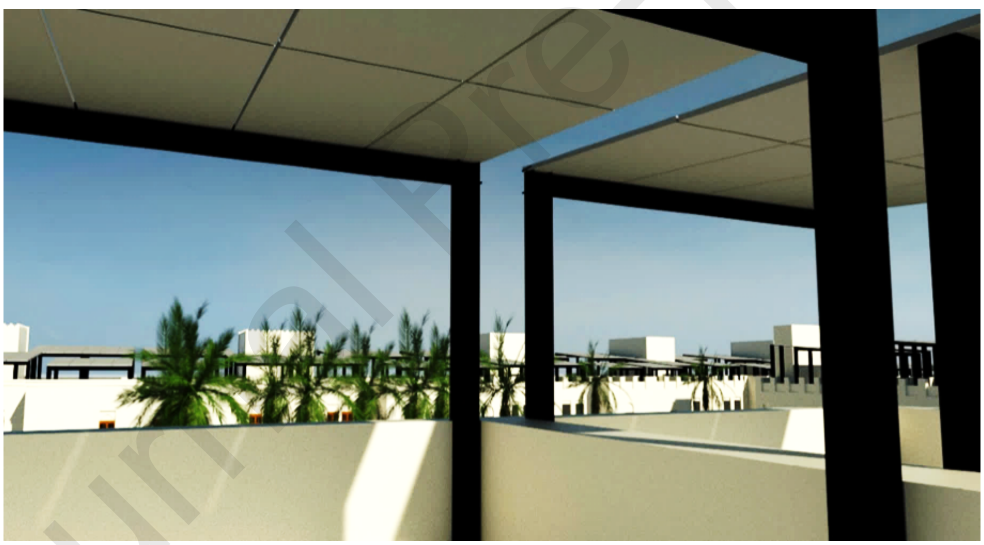
Villa type	Area of the rooftop (m^2)	Villa illustration
A1	90	
A2	100	
B1	100	
B2	100	
C2	100	

Fig.6: Main obstacles and restriction affecting PV application in roofs of Khalifa Town, Kingdom of Bahrain.

Advantage of elevating PV panels at a height of 3 m

This study envisages the use of elevated PV panels on a 3 m high metal frame to optimize the space available for the photovoltaics and minimize difficulties related to shadow avoidance. This design will play an important role in reducing the high direct solar input to the roof - which is transmitted at a later time (evening) to the interior of the house, i.e., acting as an insulation since air is a good heat insulator. The elevated PV panels will reduce the cooling load for the house and provide the luxury of having a shaded roof where the resident can enjoy their time underneath



them after fitting an artificial grass with comfortable and neat furniture Fig.7 .

Fig.7: Rendered view from one of the rooftops at Khalifa Town, Kingdom of Bahrain.

The effect of PV panel tilt on the roof

Since the orientation and inclination angle of the mounted panels have a significant impact on the output of the PV system, the panels are designed to be facing the south orientation through studying the orientation of the house, and creating various design alternatives. Alnaser [17] performed an analysis in which the incident solar power on surfaces with various tilt angles (16°, 26°, 36°) facing south was measured and found that solar gain for south facing PV panels fixed at a tilt angle equal to Bahrain's latitude of 26° N produces the highest solar electricity. However, taking into consideration the height of the installed panels, the wind load coming from the north induced on the panels as well as the overall aesthetic look of the house, it was decided to fix the panels on 5° angle facing the south orientation.

Table 3 illustrates the comparison between 26° and 5° tilt angle, calculated using PV Syst., which shows that angle 26° yields annual solar electricity of 1,811.3 kWh/m^2 while at 5° it is 1,740 kWh/m^2, i.e., angle at 26° is larger by 5%.

Table 3: Produced annual solar electricity, using PV Syst., from two tilted PV panels (26° and 5°)- both facing south, when installed on one villa at Khalifa Town, Kingdom of Bahrain.

Tilt Angle	26° angle	5° angle
PV No. of Modules	29 modules	29 modules
PV Power	13 kWp	13 kWp
Produced Energy	24.14 MWh/year	22.95 MWh/year
Performance Ratio	79.03%	80.07%

PV system power generation

The performance of the system was analyzed using the PVsyst software, where the villa units were modeled to count for the surrounding shading impact. Some of the core examples of the system output performed is presented in Table 4. The annual solar electricity generated from the PV panels of the five villas type, along with their various orientations, as well as the area utilized by the PV system on each rooftop.

Table 4: Total produced energy per villa for different types at Khalifa Town, Kingdom of Bahrain.

Villa Type	Orientation 1		Orientation 2		Orientation 3		Orientation 4		Orientation 5		Orientation 6	
	PV Area (m^2)	Total Prod. Energy (MWh/ year)	PV Area (m^2)	Total Prod. Energy (MWh/ year)	PV Area (m^2)	Total Prod. Energy (MWh/ year)	PV Area (m^2)	Total Prod. Energy (MWh/ year)	PV Area (m^2)	Total Prod. Energy (MWh/ year)	PV Area (m^2)	Total Prod. Energy (MWh/ year)
A1	60.6	21.3	60.6	21.3	60.6	21.45	60.6	21.45	65.1	22.95	65.1	22.95
A2	76.3	26.97	76.3	26.97	80.8	28.19	80.8	28.19	85.3	29.94	85.3	29.94
B1	76.3	26.92	76.3	26.92	76.3	27.03	76.3	27.03	76.3	26.19	76.3	27.00
B2	85.3	29.91	85.3	30.12	85.3	29.91	85.3	30.12	NA	NA	NA	NA
C2	80.8	28.32	89.9	31.55	76.3	26.66	76.3	26.66	NA	NA	NA	NA

The ratio of the available PV area to total roof area is about 35%, and after elevating the PV panels on a metal structure, the ratio becomes approximately 77%, i.e., having the panels elevated gives more freedom of space compared to those placed directly on the rooftop. A2 villa type is chosen as an example for addressing the findings of the system modeling for tilted PV panel deployment (Fig. 8).

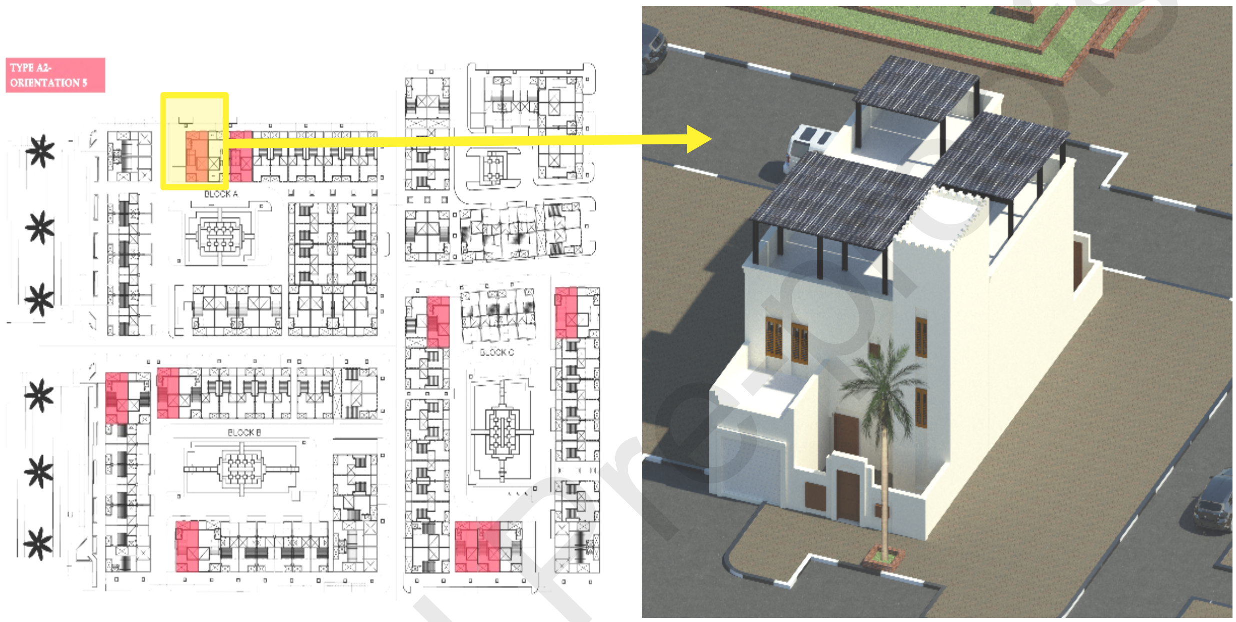


Fig.8 : A2 villa type chosen orientation for further analysis.

A summary of the monthly produced energy records is presented in Fig.9 . The simulation shows that if each house consumes approximately 5,000 kWh per month, based on Electricity and Water Authority (EWA) data. The electricity consumption per capita in the domestic sector in 2018 was 5,189 kWh, which is 62.2 MWh annually, therefore, installing 17 kW- PV system on the roof will meet almost 49% of the total resident's needs [18]. Based on the estimate that PV panels degrade at a rate of 0.6% annually then the expected electricity yield in year 25 of the installation will be 25.4 MWh which will be meeting 42% of the total resident's needs.

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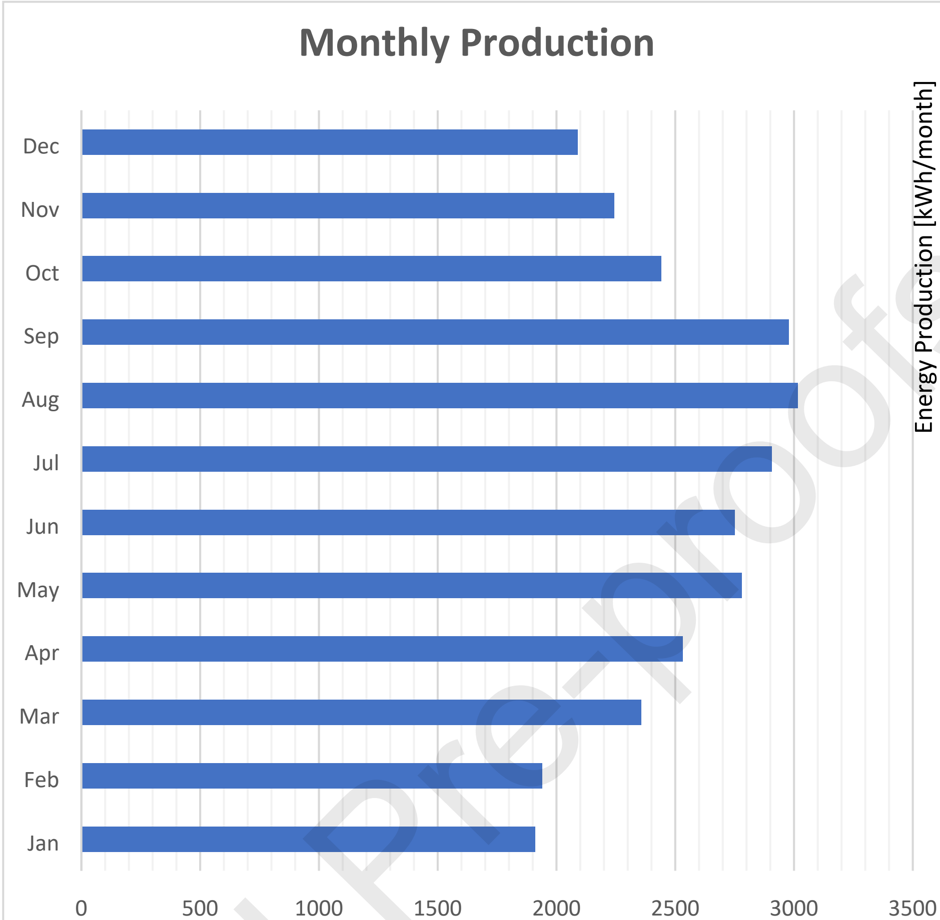

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Series1	1911	1940	2356	2532	2780	2750	2907	3016	2978	2441	2244	2089

Fig.9: Monthly produced energy for the chosen villa

Specific yield (SY) of the PV system

A 17 kWp - PV system has been used for this villa unit. The main parameters for the tilted PV system used for this villa type and orientation is provided in Table 5. The simulation shows that the system is producing about 29.94 MWh/year in which each kW is producing an average of 4.69 kWh per day, i.e., the annual specific production is 1,713 kWh/kWp. This value for SY agrees with data obtained from Kuwait (SY = 4.5 kWh/kW) [19], Abu-Dhabi, UAE, (SY = 4.7 kWh/kW/day [20], Oman (SY = 5.13 kWh/kW) [21]. Khan et al [22] concluded that the residential PV power generation capacity can generate up to 30% of total residential electricity demand. Research found that for PV applications, an average of 25% of the villa rooftops can be utilized [23].

Table 5: Overall parameter outline of PV system used for A2 villa type at Khalifa Town, Kingdom of Bahrain.

Parameter	Value
Total No. of PV Modules	38 modules
Unit Nominal Power	460 Wp
PV Array Total Power	17.48 kWp
Total No. of Inverters	1
Annual Produced Energy	29,940 kWh
Annual Specific Produced Energy	1,713 kWh/kWp
Daily Specific Produced Energy	4.70 kWh/kWp

In 2018, the Ministry of Electricity and Water launched Bahrain's first "solar home" project in Jidhaffs, with 24 solar panel installed on the rooftops, producing about 7.8 kW of electricity that is connected to the governmental power grid through a net metering scheme. The one-year data shows that the system is producing about 11.9 MWh / year, i.e. each 1 kW - PV is producing, on average, 4.6 kWh per day (SY = 4.6 kWh/kW/day)- Fig. 10.

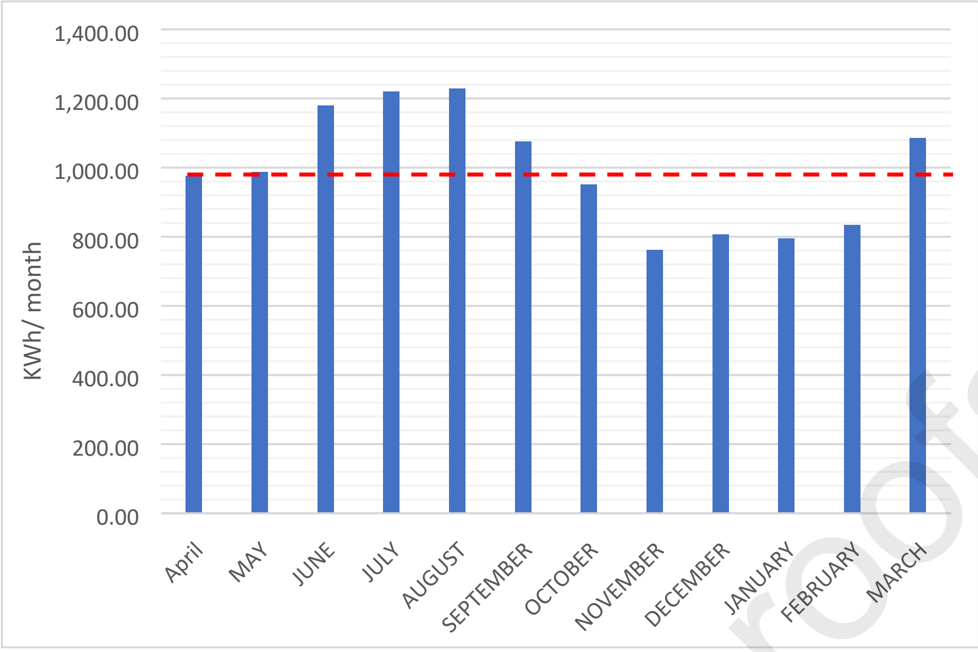

Fig. 10: Annual solar electricity from 7.8 kW rooftop Solar PV of one of four houses of Ministry of Housing project [24].

The performance ratio (PR) of the PV system

The monthly performance ratio (PR) of the PV system, which is often referred to as the quality factor [25] is demonstrated in Fig.11. The PR acts a tool to measure the quality of a PV system, independent of its location, it specifies how energy efficient and dependable the PV plant is. It can be further described as the percentage that expresses the relationship between the PV plant's real and theoretical energy outputs, where PR=Actual reading of plant output (Yf) / Calculated nominal plant output (Yr). It depicts the percentage of electricity that is eligible for grid export after accounting for energy losses.

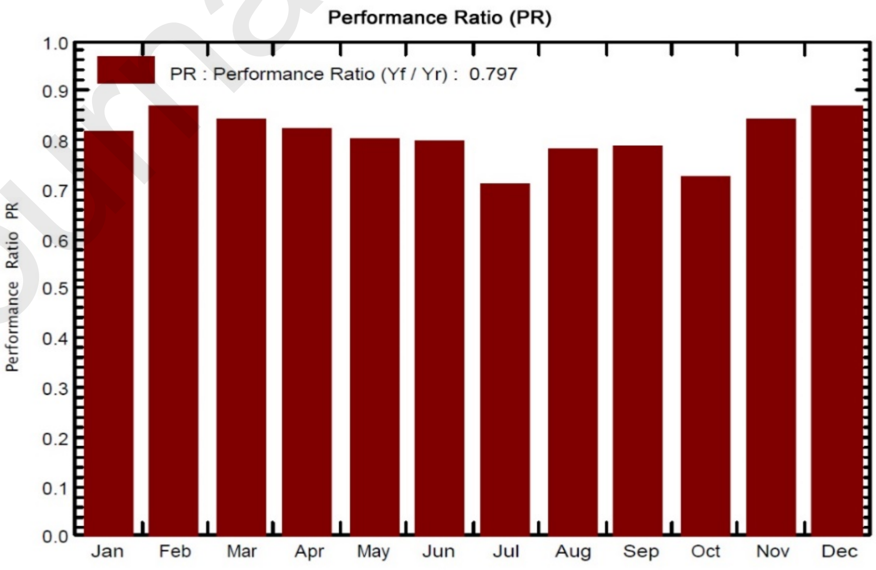

Fig.11: The Monthly performance values from A2 villa type

The closer a PV system's PR value is to 100 %, the more effective it is. The PV system for the villa has an average PR value of 79.74%, where it decreases in summer months owing it to the increased losses due to higher temperatures. A detailed flow diagram of power generated from the PV system, portraying the corresponding losses at different stages is shown in Fig.12.

Overall output from PV systems, deployed on the 120-housing unit

The results of the simulation show the overall output from the PV systems, deployed on the 120 housing unit rooftops in Khalifa Town, estimated to be about 3,129 MWh/ year for 5° tilted PV application as illustrated in Table 9, expecting it to meet 43% of the total electricity need.

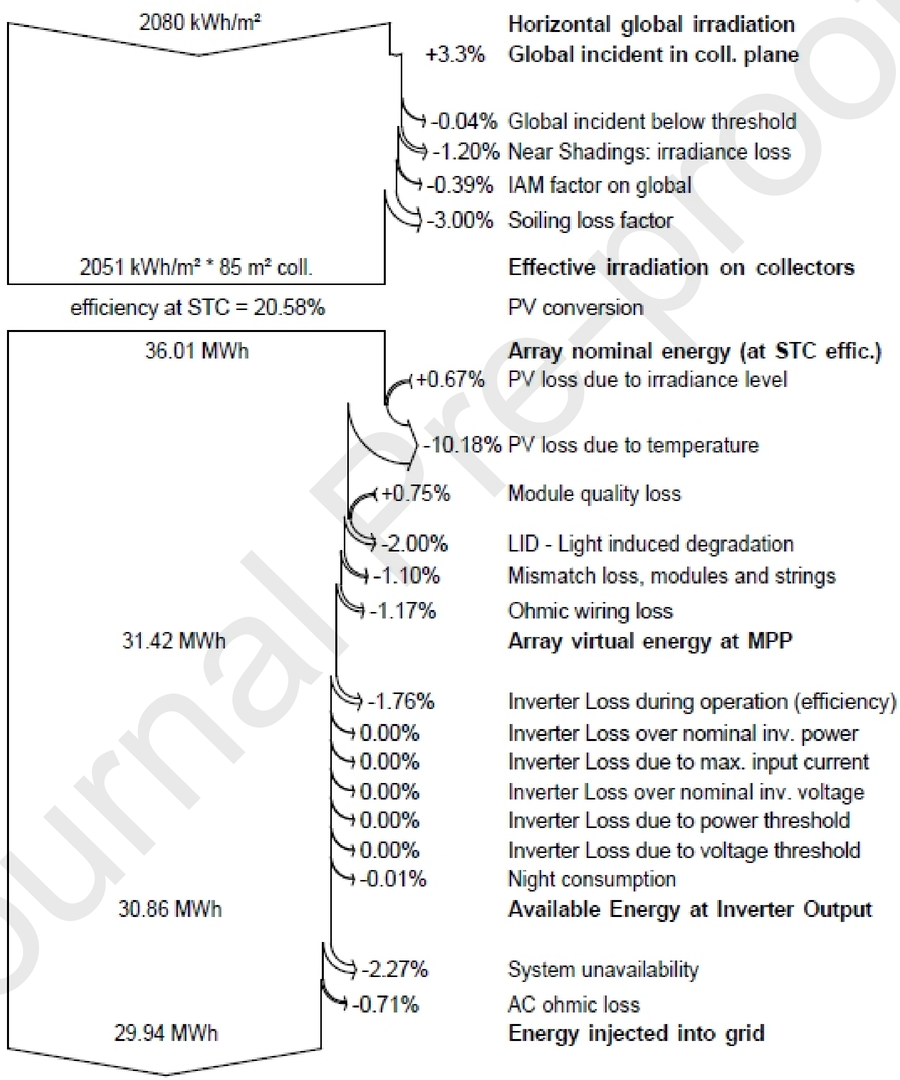

Fig. 12: PV system losses diagram [15] .

It is important to mention that in this study five different PV power capacities (12, 13, 15, 16 and 17 kW) were used for the five housing units to test the energy outcomes. This is a useful practice in planning which system to be installed based on the user's need and budget. Fig.13 shows an overview of each system and its corresponding solar electricity yield.

Table 9: Summary results of the town's generated energy from tilted PV application.

Villa type	No. of Units	Roof Area per Unit	Total Roof Area (m^2)	Total PV. Area (m^2)	Total Prod. Energy (MWh/year)
A1	44	90	3960	2733.9	964.1
A2	33	100	3300	2711.4	949.9
B1	29	100	2900	2289	805.1
B2	7	100	700	597.1	210.0
C2	7	100	700	570.3	199.7
Total Electricity Produced on the Study Area					**3,128.8**

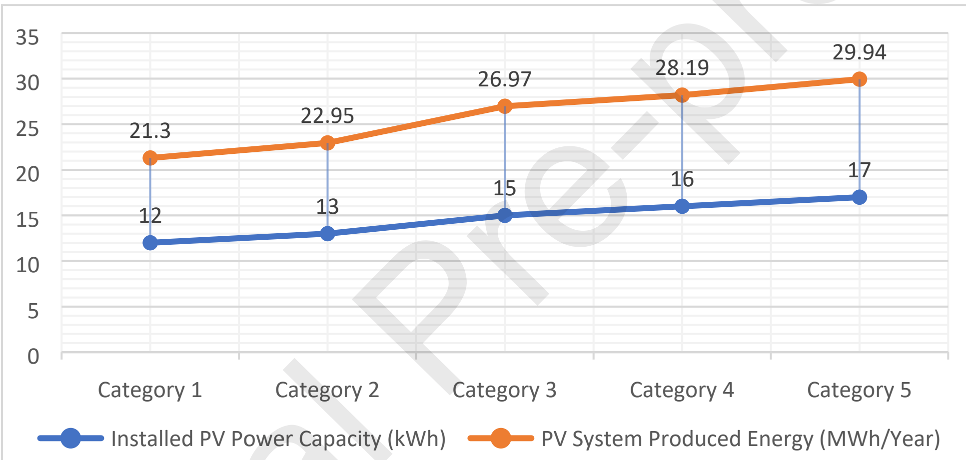

Fig.13 : Solar electricity yield from various PV installation (12, 13, 15, 16 and 17 kW) - lower line (blue color) with the respective annual solar electricity produced - upper line (red color).

PV system economic impact

Financial decisions will always prevail where the household needs to know the payback period (PBP) of the investment, i.e., when will electricity be generated at optimum cost. The resident will be interested to know whether installing 17 kW - PV is a good investment or not, especially when PV panels can have a high initial capital cost; they are about BD 0.4 per W (BD 415 / kW) at 2021 prices, with an operational life of 25 years. However, technology is reducing the capital and installation cost, and improving the efficiency of PV panels; technological obsolescence must therefore be considered. A factor is the time value of money and the selection of the nominal and real discount rate to be used when undertaking a whole life cost appraisal (WLC). Such WLC considerations should include operational maintenance, and repairs and refurbishment. The PBP and net present value (NPV) analysis, were used to evaluate the economic impact of such projects, with Villa A2 as an example.

Table 10 shows the approximate initial cost of the system, which includes the initial capital cost of PV panels, auxiliary components such as charge controllers, inverters, and wiring, miscellaneous works, overheads, and profit, as well as the cost of structure used. Rates for PV device components were collected by quotations from local vendors.

Table 10: Initial investment calculation.

Item	Brand	Quantity	Unit Price (BD)	Item Cost (BD)	Total Sale Price (BD)
PV modules	Jinko Solar	38	43	1,634	1,634
Inverters	Huawei	1	850	850	850
Structure	Chiko	1	440	440	440
BOS components	General	1	450	450	450
Electrical works	NA	1	350	350	350
Mechanical works	NA	1	300	300	300
Miscellaneous	General	1	640	640	640
				Overheads	1,750
				Profit	850
				Total	**BD 7,254**

The electricity tariff in Bahrain is applied as per usage, either domestic or non-domestic (commercial). Domestic tariffs are divided into three categories as seen in Table 11, i.e., 3 fils per kWh, 9 fils per kWh and 16 fils per kWh based on 2021 current prices.

Table 11: Applicable electricity tariff for Bahraini domestic usage in Bahrain [18] .

Categories for Domestic Tariff for Bahrainis having one account (Subsides).		Electricity consumption unit	Monthly fixed charge (BD)	Electricity usage charge (Unit) Years 2016-2019
Consumption Units	First 3,000	Kilowatt- hour (kWh)	1.000	3 Fils
	3,001-5,000			9 Fils
	Above 5,000			16 Fils

Note that 1fils = USD¢ 2.6 ; 9 fils = USD¢23.4, 16 fils = USD¢ 41.

i. The Net present value (NPV)

The Net present value (NPV) is a dynamic tool used to assess the viability of the PV project. As NPV > 0, it means that the projects will gain if they fulfill the requirements set by the benchmark yield; in other words, the investment in this project is economically viable. The NPV is calculated using the following [26]:

$$\mathrm{NPV} = V_0 + \sum_{t=1}^{n} \frac{V_t}{(1+d)^t},$$

where V_0 is the cash flow value at present, V_t is the cash flow value at the end of period t, n is the number of periods in other the project duration which is equal to the warranty period of the PV system (25 years), and d is the discount rate which was assumed to be 3.5% in this study. The findings of the NPV analysis are illustrated in Table 12.

Table 12: NPV analysis calculations for installing 17 kW -PV system at Khalifa Town

Total Investment = BD 7,254		**Unit Production=29,944 kWh**	
Unit Price= BD 0.029		**Inflation rate, d = 3.5%**	
Years	**Production (kWh)**	**Estimated cash flow**	**NPV (BHD)**
1	29,944	868	839
2	29,195	847	818
3	29,020	842	813
4	28,846	837	808
5	28,673	832	803
6	28,501	827	799
7	28,330	822	794
8	28,160	817	789
9	27,991	812	784
10	27,823	807	780
11	27,656	802	775
12	27,490	797	770
13	27,325	792	766
14	27,161	788	761
15	26,998	783	756
16	26,836	778	752
17	26,675	774	747
18	26,515	769	743

The table shows that installing 17 kW -PV will make a good investment, i.e., the revenue will be nearly BD12,000 (USD 31,000) if the cost of kWh is purchased by the utility (EWA) for 29 fils (USD¢7.5) , otherwise it will be a loss investment (BD – 5,270 or USD 13,702) if it is purchased for 3 fils (USD¢0.8) from EWA. If inverters are expected to be changed every 10 years, the final revenue would be about BD10,200 (USD 26,520) since each invertor costs BD 850 (USD 2,210). In other words, installing 17 kW solar PV on housing rooftop at a cost of BD 7,254 will save the owner paying approximately BD 10,200 (USD 26,520) for supplying solar electricity for 25 years, as highlighted in the cash flow diagram in Fig.14.

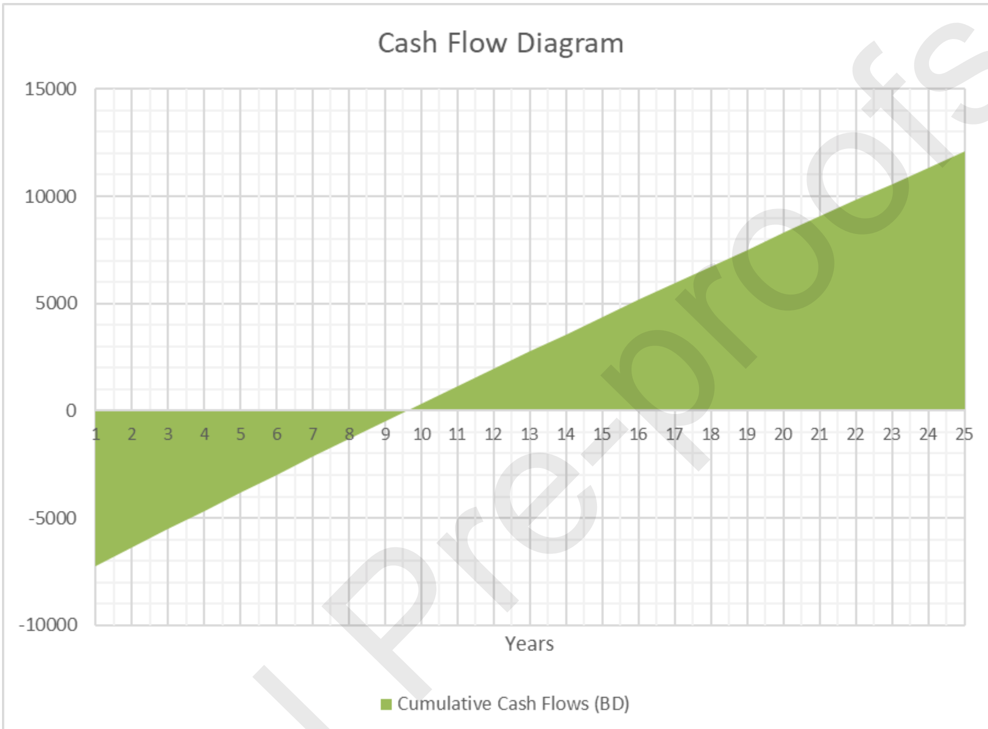

Fig. 14 : Cumulative savings over 25 years in investing in 17 kW -PV system on villa roof top at Khalifa Town, Kingdom of Bahrain.

ii. Payback Period

The payback period is defined as the amount of time it takes for an investment to be fully repaid or amortized. It identifies how long it would take for the cumulative net cash flows to equal the initial expenditure. In this study, the payback period has been estimated twice, once while considering the tariff to be 3 fils (USD¢=0.8) (subsidized) and the other using the actual cost of electricity which is 29 fils (USD¢7.5). The cash flow diagram developed (Fig 14) as well as using the following relationship:

PBP = [Cost of total PV system / System saving (solar electricity produced in kWh x tariff rate)]

It can be observed that PBP of the PV system when tariff is 29 fils (USD¢7.5) is found to be 9.6 years compared to PBP of 83.5 years if the tariff used is 3 fils! This indicates that the low kWh tariff in Bahrain provides no incentive to use PV for electricity production at Khalifa Town as the payback period (PBP) is too high.

iii . Maintenance

Solar panels require minimal maintenance to ensure proper and solar electricity production for the home. The most common type of maintenance required is cleaning. Our proposed PV installation will requires using a 3 m ladder to reach the panels to wash up dirt and debris can be collected on the panels, especially during storms or extended periods without rainfall. This is a big challenge to the household, otherwise an annual loss of solar electricity may reach 12% annually [27]. Annual inspection is another task that must be done, where a professional must inspect the panels regulators, invertors, wiring, etc. If no fault in the electronic component, then the cost per kWh of solar electricity will not jump high.

Environmental impact

According to the International Energy Agency statistics [14], Bahrain's annual GHG emissions equal 30.2 million tons of CO_2 in 2018, equivalent to around 20 tons per capita. Electricity and heat producers sector account for more than 87% of CO_2 emissions where the residential sector alone consumes more than half of the electricity produced and accounts for 20% of the country's overall CO_2 emissions. Therefore, it is important to invest in the renewable energy to minimize CO_2 emissions.

The study shows that the amount of generated electricity from the installed rooftop PV system of the 120-housing unit is 3,129 MWh, which is found to equal saving about 2,422 ton of CO_2 emissions as each 1 kWh equal emission of 0.774 kg of CO_2 when using natural gas. This amount of CO_2 saving is equal to saving 979,377 kg of oil, or 7,201 barrels of oil (1 barrel = 136 kg of oil) [28]. Thus, the total CO_2 emissions saving for the total 1,724 units of phase 1 in Khalifa Town is estimated to be equal 34,794 tons of CO_2 emissions, i.e., reducing about 21% of the CO_2 emissions in this city. Table 13 compares the findings of our study with a similar study in Sohar, Oman [13]; both locations are in arid zone and give close figures which validates both systems proposed.

Table 13 : Comparison between the findings of this study with other studies in GCC countries .

Project	Latitude and longitude	Size of Installation	Specific Yield kWh/kW/day	Cost of solar kWh USD¢	Pay-back Period (Years)
Khalifa Town in Bahrain	26.2° N, 50.6° E	17.5 kW Rooftop	4.7	7.5 (If each kWh is purchased @7.9)	9.6
Sohar City in Oman [13]	24.4° N, 56.7° E	1.4 kW Rooftop	5.1	4.5	11
Kuwait City [19]	29.4° N, 48.0° E	21.6 kW_p Rooftop	4.5	NA	NA
Abu Dhabi [20]	24.5° N, 54.4° E	14.6 kW System 6	3.9	N.A	4.2
Riyadh [29]	24.7° N, 46.7° E	124 kW	4.5	5.4	NA

Major Findings

Elevating the PV panels on a metal structure will increase the space in the roof to reach 77% of roof area, i.e., total net area of 8900 m^2, compared with previously, 35% with total area 4046m^2. This arrangement has several advantages, among them is reducing the high direct solar input to the roof, which is then transferred to the interior of the building later (evening), i.e., serving as insulation. According to previous research on rooftop energy savings due to shading, it was found that nearly half of the solar gain on the roof slab could be eliminated through this configuration (shading with PV panels), resulting in 1.7 to 7% reduction in the building's average annual energy consumption [30 -32].

Although energy generated by mounting the panels at a 26° angle produces more solar electricity than if panels were at a tilt angle of 5°, there are two reasons to opt for the change:

1- It will reduce the wind load placed on the elevated tilted PV panels as was discovered on previous projects in Bahrain where the wind load was calculated and panels placed at 10° angle [33] .

2- It will maintain the building's overall architectural appearance - as shown in Figs. 15 and 16- which illustrates how the proposed installed PV system would look.

Fig.15 : Rendered views of the proposed PV Installed system in Khalifa Town.

Fig.16: Rendered views of the proposed PV Installed system in Khalifa Town.

Conclusions

The rooftop design of the housing units in Khalifa Town revealed significant restrictions for PV application due to a variety of structural and architectural obstacles that allowed about 35% of the available roof area, depending on the building typology, to be utilized by the PV application. As a result, system efficiency and space utilization have been optimized through placing the 5° tilted PV panels on elevated metal structure as shown in Fig.17.

Fig.17 : Cross- sectional view through one of the town's blocks.

Modelling and simulation through PVsyst software shows a net annual generation of 3,129 MWh for the 120 housing units, i.e., 44,953 MWh for 1724 housing units which is enough to satisfy about 43% of the overall town's electricity needs.

Economically, it is concluded that the comparatively low kWh tariff in Bahrain will not encourage the installation of solar electricity photovoltaic systems on rooftops. The pay-back period (PBP) was found to be too long (83.5 years) compared to 9.6 years for 29 fils (USD ¢7.5) tariff. Thus, installing PV systems on a rooftop would be appealing only if the client received financial assistance or a low-interest loan, and the government purchased the provided solar energy from the rooftop at a considerable cost between 75 fils (USD ¢19.5) to 86.3 fils (USD ¢ 23) by introducing Feed-In-Tariff policy. This will inspire home builders to make roofs more suitable for PV applications, allowing for maximum roof use with no obstacles.

Using PV in buildings will greatly boost their environmental efficiency, with annual greenhouse gas emissions in Khalifa Town lowered by up to 34,794 tons of CO_2, which is equivalent to a reduction of around 21% of the town's CO_2 emissions.

Future research work is necessary; this will include installing 17.5 kW -PV system on a roof top on one of the villas at Khalifa Town and collect all the related data and conduct the analysis to compare the outcome of this feasibility study with an actually measured data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors thanks University of Bahrain, Arabian Gulf University and University of Reading for preparing the necessary facilities to conduct this study. Special thanks to Prof Dr Eslam Elghonaimy for his advice and suggestions and to Almoayed Solar Company, Bahrain, for providing necessary information on PV installation and valuable data on first domestic house with Solar PV installation on rooftop.

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Declaration of interests

☐The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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W E Alnaser reports article publishing charges was provided by Arabian Gulf University. W E Alnaser reports a relationship with Arabian Gulf University that includes: employment. There is no conflict of interest

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