

RESEARCH ARTICLE

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The performance of four domestic rooftop 7.8 kW – PV in the Kingdom of Bahrain: toward low building emission

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Abstract. This paper reports the performance of four domestic houses at different locations in Bahrain, each have 7.8 kW of PV on the roof, and all panels are tilted at 12° , but the azimuth of the panels (orientation) in these houses varies slightly from south ($\pm 10^\circ$); depending on roof space availability and building surroundings. The data of year 2019 have been used because all these domestic houses were monitored, maintained, and cleaned by an assigned company from the government. The annual solar electricity generated was 11,329 kWh, 11,448 kWh, 10,978 kWh, and 9995 kWh for houses # 4, # 2, #1, and # 3, respectively. The annual Specific Yield (SY) obtained was 1468 kWh/kW, 1452 kWh/kW, 1407 kWh/kW and 1254 kWh/kW for houses # 2, #4, # 1, and # 3, respectively; this makes the daily average SY equals to 4.02 kWh/kW, 3.98 kWh/kW, 3.85 kWh/kW, and 3.43 kWh/kW, respectively. The average performance ratio (PR) of each PV system were found to range from 75.1% to 65.6%. The PV system performs better in house #4 due to its azimuth PV panels' angle (orientation) which is closest to the south direction. A polynomial equation is established, relating the month number (X) and the monthly average of monthly solar electricity generated as well as the monthly specific yield (Y). This work shows that installing a 7.8 kW_p of PV on the roof of all residential building in Bahrain will reduce the total CO₂ emission in Bahrain by 39.0% (4.637 tons) per year, saving 38,567 ft³ of natural gas. This is a step towards low-carbon building; in an attempt to make Bahrain a zero carbon by 2060.

Keywords: 7.8 kW-PV / solar electricity generation / specific yield / performance ratio

1 Introduction

Bahrain has kicked off a tender to award a 20-year contract to a local or international company to build, operate and transfer (BOT) and maintain a grid-connected solar project with a minimum capacity of 72 MW in the Southern of Bahrain [1]. There is over 250 MW in planning or execution, to be delivered by 2025.

The first non-domestic 4kW PV – panel and zero emission building installed in Bahraini building was in 2010 to provide solar electricity [2,3]. This installation was part of 6.9 kW hybrid renewable energy project (4 kW solar PV, 1.7 kW wind, 1.2 kW hydrogen fuel cells) managed by the Bahrain Petroleum Company (Bapco). The concept of zero emission building had become in focus in GCC countries. Now, the largest zero emission building in GCC at University of Dubai, which achieved the title of LEED-certified first net-zero energy building in the region. It was named the first net-zero energy building in the region after CleanMax commissioned a 1.7 MW ground mounted solar plant at its campus in Academic City [4], and it is the second university in the world to meet all energy needs from solar farm [5] with an annual solar electricity output

of 2.72 GWh and saving carbon emission abating of 2040 tons per annum [4] – assuming that each kW – PV will produce 4.4 kWh (specific yield, SY = 4.4 kWh/kW/day) and assuming that each kWh from solar electricity saves 0.75 kg of CO₂ emission.

The second PV installation was made on a sponsored building at Awali in 2014 by Bapco, refer to references [6,7]. There are 36 PV panels on the roof of this building, each having 240 W_p, so the total installed power is 8.64 kW. The panels' orientation is 225° from the north and has a tilt angle of 25° although the latitude of Bahrain is 26.138°N and latitude 50.88°E . The total area of PV panels on the roof is about 60 m².

Subsequently, the first large PV installation in Bahrain (5 MW) was in 2014 [8–11]. This PV installation is located at Princess Sabeeka Park in the city of Awali (26.1°N , 50.6°E). The minimum and maximum values of the monthly average daily global solar radiation in Awali were 4.00 kWh/m² and 4.79 kWh/m² in January and July in 2015, respectively [3].

In February 2016, Tatweer Petroleum company, Bahrain, installed a 1 MW solar PV, ground installation, connected to the electricity grid of Tatweer to provide enough electricity to meet the total energy requirements of the company's headquarters in the region [12]. Later on, on 30th December 2019, Tatweer Petroleum installed another

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ground 3 MW Solar PV generating more than 5400 MWh per year which is equivalent to the energy used by 300 Bahraini homes, bringing the company's use of renewable energy to 6% [13].

Nearly 46 MW of solar PV installation are either executed or planned to be in operation by 2024 in Bahrain [14]; Y&K Company is the contractor of nearly 18 MW PV solar projects.

As part of Bahrain vision 2030 and part of its worldwide commitment to have a renewable energy share of 10% by 2035 which is explained in detail in [15,16], as well as its endeavor to have zero emission by 2060 [17], the government had sponsored the installation of 10 PV domestic houses rooftop, each 7.8 kW, feed to the national grid [18].

The aim of this paper is to report the performance of four 7.8 kW solar PV systems installed on the rooftop of domestic houses at different locations in Bahrain where all panels are tilted at 12° , with slightly azimuth angles ($\pm 10^\circ$ from south); depending on roof space availability and building surroundings. The result assist policy makers to apply such a solar PV system to nearly 140,000 domestic houses taking into consideration all the drawback and cons. This is a step towards converting the current domestic houses to be a low carbon building in an attempt to make Bahrain a zero carbon by 2060 as Bahrain has adopted a number of initiatives to become carbon neutral, including quadrupling the mangrove trees [19].

2 Methodology

Bahrain had installed 10 domestic houses, each with 7.8 kW_p – PV system on the roof at different locations in Bahrain to evaluate the spatial, social and financial effect. Unfortunately, only 4 houses were monitored carefully by Almoayyed Solar Company (ASC) which is a division of Almoayyed International Group specializing in Energy Service and Energy Auditing for improving overall energy performance of Commercial, Industrial and Residential sectors. All of these four houses were handled and managed by ASC.

All solar electricity is recorded and tabulated by ASC. The 7.8 kW_p – PV system of the house consist of the following:

1- Twenty-four (24) polycrystalline silicon (poly-Si) PV panels, manufactured by Jiangsu Seraphim Solar System Co. Ltd. Model SRP-325-6pA, made in China. Based on STC: 1000 W/m², Air Mass (AM) 1.5, $T = 25^\circ$. The technical data of each panel is: power rating of 325 W, current at $P_{\max}$ is 8.72 A, voltage at $P_{\max}$ is 37.3 V, short circuit current of 9.03 A, open-circuit voltage is 45.7 V, maximum string voltage is 1000 V_{DC} and maximum series fuse rating is 15 A. The weight of each panel is 23 kg, dimension of 1.96 m × 0.99 m × 4 cm.

Due to roof restriction and surroundings, there were limitation for the panel's orientation; therefore, the azimuth of each PV panels in each house was made different (instead of 180° – due south). The azimuth angle of the PV panels in all houses is about 160° , with variation of $\pm 10^\circ$. All panels in all PV panels in house were fixed at a

titled angle of 12° with the horizontal (instead of 26° – which is the latitude of Bahrain). This is to avoid wind force stress on PV panels because they were anchored on Concrete Foundation that can withstand wind speed no more than 30 m/s (110 km/h). The flow of turbulent air under the panel may cause serious stress on the stability of the panels (Fig. 1). House # 3 suffers from shading effect caused by a very large desalination tank (silo) which is located at azimuth from 230° to 270° (west-south to north-west) and higher than the roof level by nearly 10 m (Fig. 2). This led to less solar electricity yield.

2- Inverter: The inverter features a simple, standardized mounting system, making installation and maintenance easy and simple. The solar DC connection area is separate from the power stage set compartment, with both being installed separately. The inverter allows for data communication package with fully integrated datalogging, WLAN, Ethernet, energy management, web server and a range of interfaces. The inverter is connected to the internet by network cable or WLAN – without additional cabling – and grants you an overview of how the PV system is operating. Connection to third-party components is provided by means of interfaces such as Modbus TCP SunSpec, Modbus RTU SunSpec or Fronius Solar API (JSON). The open interfaces can also be operated in parallel to the Fronius Solar.web. The inverter has the following output features. AC nominal output ($P_{ac,r}$) = 7000 W, Max. output power ($P_{ac,max}$) = 7000 VA, AC output current ($I_{ac,nom}$) 10.1 A, grid connection ($U_{ac,r}$) 3~ NPE 400/230, 3~ NPE 380/220 V, AC voltage range ($U_{min} - U_{max}$) 150–280 V, frequency 50/60 Hz, frequency range ($f_{min} - f_{max}$) 45–65 Hz, total harmonic distortion < 3%. The dimensions of the inverter is 431 mm (width), 645 mm (height), 204 mm (depth), having a weight of 21.9 kg. The inverter design is “transformerless”, regulated air cooling valid for Indoors and outdoors installation. It is suitable for ambient temperature from -25°C to $+60^\circ\text{C}$, with maximum efficiency (PV-grid) of 98% and MPP adaptation efficiency is >99.9% [19].

3- DC SPD box: It is a DC surge protective device to protect the DC electric system from surge. Also, it allows replacement of the protective metal oxide varistor (MOV), i.e., a voltage dependent device which has an electrical behavior similar to back-to-back Zener diodes. This ensures convenience and reduced cost [19].

4- PV array junction box: It also referred to as PV combiner boxes. It collects DC power from the 7.8 PV strings with blocking diodes on each string for protecting panels from reverse current flow. The collected power is then transferred to the inverter to be converted into AC [19].

5- Smart PV meter: The smart PV meter, also called the Renewable Energy Meter, measures the solar energy generated from the solar PV system. In contrast to a bi-directional billing meter, which measures only the energy being sent back to the grid but not the total solar produced by the PV system. Net-Metering is a billing mechanism, which allows the plant operators to feed electricity they do not use back into the grid and credits solar PV system owners for what they add to the grid in terms of kWh credit (no money, but energy credits). The PV meter is installed as part of the PV system and is used to determine the self-consumed part of the solar power in



Fig. 1. The PV panels on the rooftop of the first 7.8kW – PV domestic building (House 4 #108) in Bahrain were anchored on Concrete Foundation that can withstand wind speed no more than 30 m/s (110 km/h).



Fig. 2. A large desalination tank (silo) – located at azimuth from nearly 240° to 280° (west-south to west) and higher than the roof level by nearly 10 m causes shading effect to the PV rooftop system on House #3 which led to less solar electricity yield.



Fig. 3. The main components of PV power electronic systems for PV array installed at all 7.8 kW – PV domestic buildings (houses # 1 to #4) in Bahrain. These components are Smart PV meter, PV array junction box, DC SPD box and solar inverter.

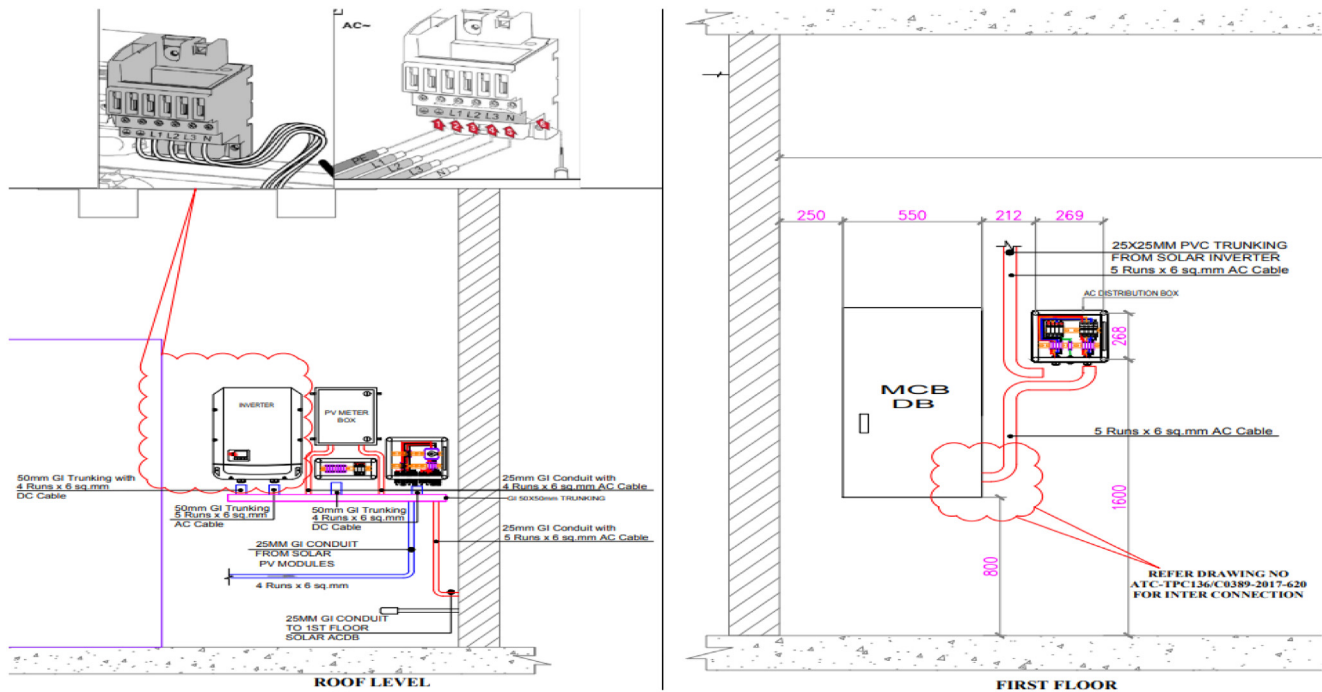


Fig. 4. The diagram of the PV electric systems installed at all 7.8kW – PV domestic building (houses # 1 to #4) in Bahrain.

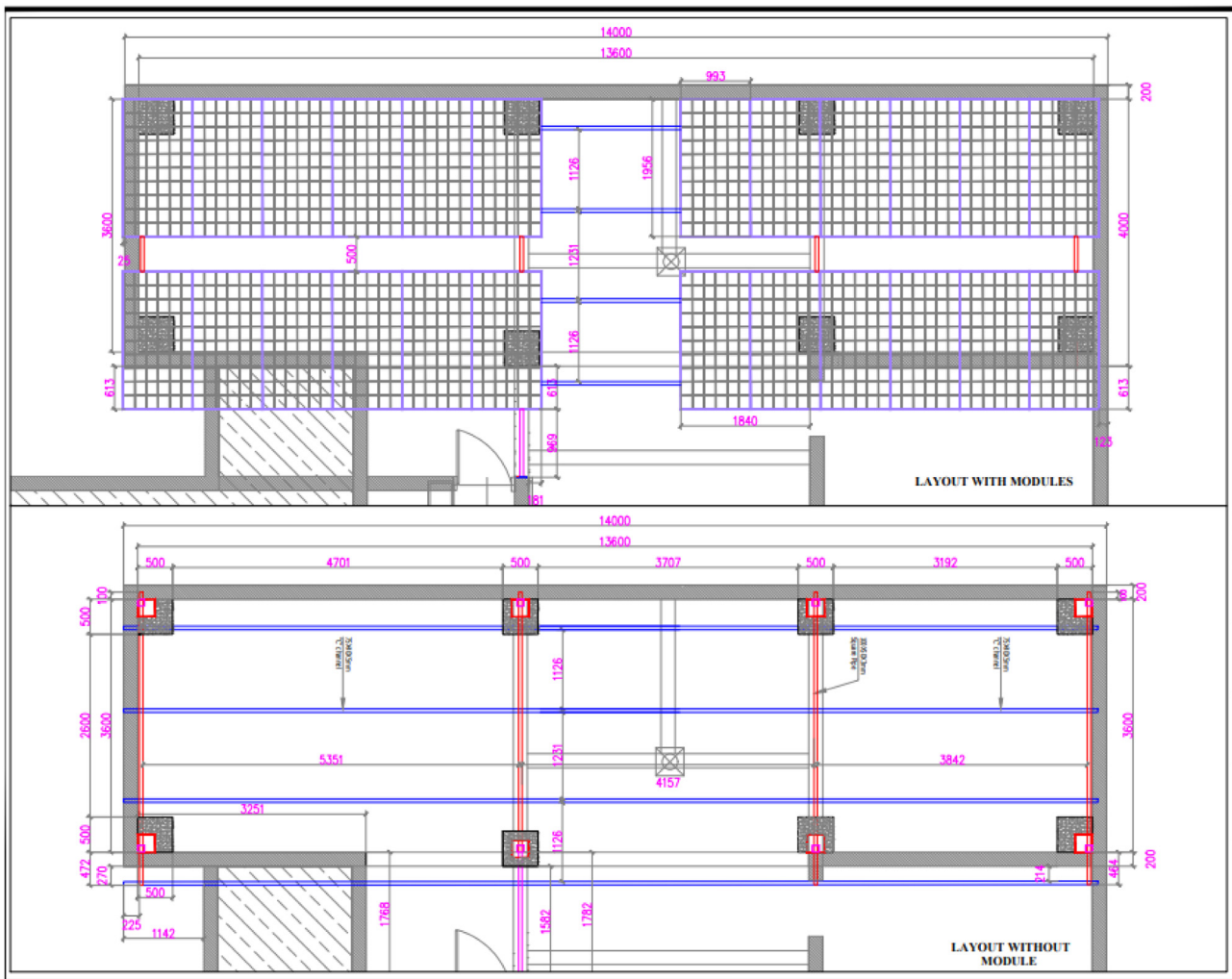


Fig. 5. The layout of the first 7.8 kW – PV domestic building (House 4 #108) in Bahrain with PV (top) array and without PV array (bottom). Nearly all houses have the same layout.

kWh in conjunction with the data from the billing meter. The billing meter is owned by EWA who are the grid system operator [19].

Figure 3 illustrates the 4 components of PV electronic systems in all four houses and Figure 4 shows the electric connections of the system. Such system is made to all prototype domestic 7.8 kW Solar PV in Bahrain. It is planned to charge each household about BD 3500 (USD 9300) for the whole system.

Figure 5 shows the layout of the roof of house #4, as an example, without PV array and with PV array. It is very clear that the PV had occupied about 20% of the roof. This has advantage of providing shade on the roof and hence less heat transfer from roof to rooms through ceiling but also has the advantage of allowing space for social gathering or activity on the roof as the PV panels were raised off the roof deck.

Figure 6 shows the actual layout of the roof from top of the PV panels (top right). The pictures belong to House #4–which was the first to operate partially by solar PV.

All the recorded data of solar generation and specific yield were stored and processed at ASC and has kindly been provided to the author in Excel sheets. The data were tabulated and analyzed statically.

3 Results and discussion

3.1 Performance of PV solar electricity generation

3.1.1 House #1

According to the raw data provided for the solar electricity generation of this domestic building which uses solar 7.8 kW_p – PV in Bahrain, in 2019, the maximum obtained solar electricity, in a particular day, was 47.07 kWh (on 23 April 2019), followed by 43.77 kWh (on 24 April 2019).

Figure 7 shows the monthly solar electricity (in kWh) in 2019 produced from 7.8 kW solar PV system at rooftop for the House.



Fig. 6. The actual layout of the PV panels of the first 7.8 kW – PV domestic building (House #4) in Bahrain. Top of PV panels (top right), below the PV panels (top left), during the official inauguration of the project (bottom right) of the house and view of the installed of the roof PV from ground and from neighborhood (bottom left).

Table 1 shows that total solar electricity generated in year 2019 was 10,978.03 kWh (full year) with a monthly average of 914.84 kWh. It also shows that May and June are the months that produces high monthly average, i.e. 1109.27 kWh and 1096.66 kWh, respectively.

3.1.2 House #2

According to the raw data provided for the solar electricity generation of this domestic building which uses solar 7.8 kW_p – PV in Bahrain, in 2019, the maximum obtained solar electricity, in a particular day, was 46.14 kWh (on 23 April 2019), followed by 44.93 (on 24 April 2019).

Figure 8 shows the monthly solar electricity (in kWh) in 2019 produced from 7.8 kW solar PV system at rooftop for the House. Table 2 shows that total solar electricity generated in year 2019 was 11,447.80 kWh with a monthly

average of 953.98 kWh. It also shows that May and June are the months that produces high monthly average, i.e., 1152.56 kWh and 1135.41 kWh, respectively.

3.1.3 House #3

According to the raw data provided for the solar electricity generation of this domestic building which uses solar 7.8 kW_p – PV in Bahrain, in 2019, the maximum obtained solar electricity, in a particular day, was 46.8 kWh (on 23 April 2019), followed by 43.93 kWh (on 24 April 2019). Figure 9 shows the monthly solar electricity (in kWh) in 2019 produced from 7.8 kW solar PV system at rooftop for the House.

Table 3 shows that total solar electricity generated in year 2019 was 9995.38 kWh with a monthly average of 832.95 kWh. It also shows that May and June are the months that produces high monthly average, i.e. 1067.78 kWh and 1057.31 kWh, respectively.

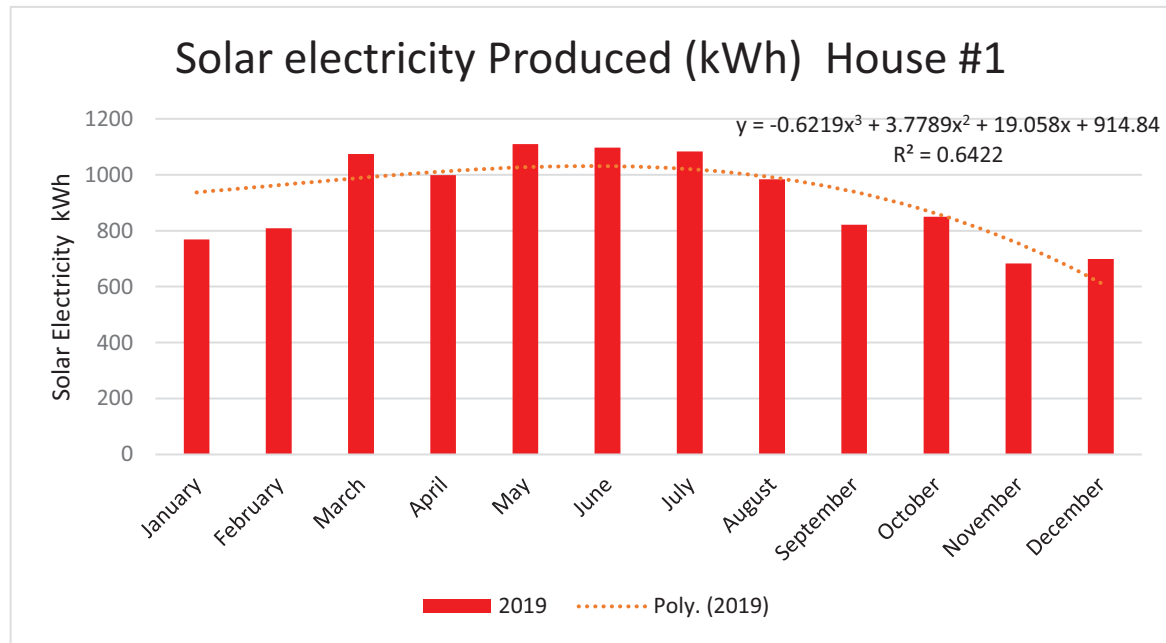


Fig. 7. The monthly solar electricity (in kWh) in 2019 produced from 7.8 kW solar PV system at rooftop for domestic building in Bahrain (House #1).

Table 1. The monthly solar electricity produced and the specific yield from 7.8 kW – solar PV system at rooftop for house #1 in Bahrain in 2019.

House #1		
Year 2019	Solar electricity (kWh)	Specific yield (kWh/kW)
January	769.23	98.61
February	808.87	103.7
March	1074.17	137.69
April	999.2	128.1
May	1109.27	142.23
June	1096.66	140.61
July	1082.92	138.79
August	983.83	126.12
September	821.66	105.34
October	849.43	108.92
November	683.38	87.61
December	699.41	89.68
Total	10,978.03	1407.4
Ave	914.84	117.28

3.1.4 House #4

According to the raw data provided for the solar electricity generation of this domestic building which uses solar 7.8 kW_p PV in Bahrain, in 2019, the maximum obtained solar electricity, in a particular day, was 47.8 kWh (on 14 April 2019), followed by 47.6 kWh (on 23 April 2019). Figure 10 shows the monthly solar electricity (in kWh) in 2019 produced from 7.8 kW solar PV system at rooftop for the House.

Table 4 shows that total solar electricity generated was 10,728.58 kWh with a monthly average of 894.05 kWh. It also shows that May and July are the months that produces high monthly average, i.e. 1135.59 kWh and 1128.12 kWh, respectively.

Figure 11 shows the measured mean daily global solar radiation at Bahrain International Airport (Lat 26° 16'N – Long 50° 39'E, Height 2 m) while Figure 12 shows the mean monthly solar global solar radiation. The total monthly solar potential in 2019 was 5393.3 Wh/m² and average monthly solar radiation was 449.4 W/m².

Surprisingly, in all houses in all seasons, no daily solar yield had researched more than 50 kWh, in 2019. The total area of all PV system is 46.6 m², therefore, 50 kWh means a useful incident solar radiation of only 102 W/m² if the sunshine duration is 10.5 hrs; this means the efficiency of the PV panels never exceeded 17% otherwise it should lead to solar radiation equal to 600 W/m²—which is the highest daily solar radiation in Bahrain. This clearly attributed to effect of the solar PV tilt angle (12°) – as the closer to latitude of the country the more solar incidence throughout the year with peak in spring and autumn – and azimuth (160°) as if the PV panels tilt angle is 26° and their azimuth is 180° would definitely lead to largest daily solar electricity in June–July [7].

Figure 13 shows the monthly average solar electricity, in 2019, produced from the four domestic houses in Bahrain, each having 7.8 kW – PV at roof top with tilt angle 12° but varies slightly in the azimuth angle of the PV panels.

The following polynomial correlation is found between the solar electricity (X) in particular month (Y), with relatively high correlation coefficient ($R^2 = 0.861$) i.e., solar electricity generated, $Y = 1.678x^3 - 42.5x^2 + 280.76x + 537.86$ (kWh).

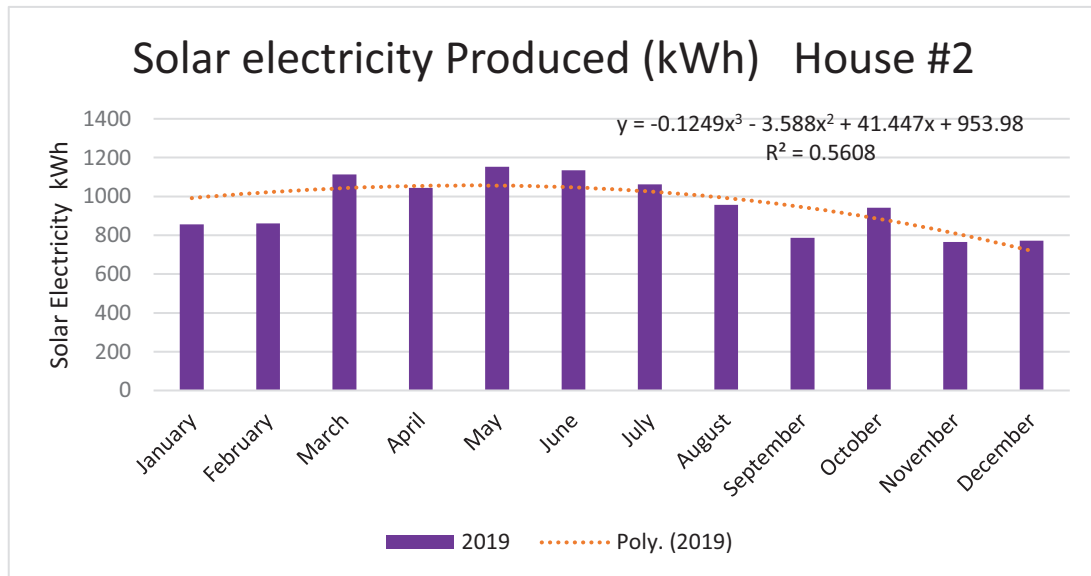


Fig. 8. The monthly solar electricity (in kWh) in 2019 produced from 7.8 kW solar PV system at rooftop for domestic building in Bahrain (House #2).

Table 2. The monthly solar electricity produced and the specific yield from 7.8 kW – solar PV system at rooftop for house #2 in Bahrain in 2019.

House # 2		
Year 2019	Solar electricity (kWh)	Specific yield (kWh/kW)
January	856.2	109.78
February	861.67	110.48
March	1113.59	142.76
April	1044.33	133.9
May	1152.56	147.79
June	1135.41	145.56
July	1061.93	136.15
August	957.08	122.7
September	786.26	100.82
October	941.38	120.68
November	764.91	98.07
December	772.48	99.02
Total	11,447.80	1467.71
Ave	953.98	122.31

For example, to estimate the expected solar electricity in March ($x=3$) and in September ($x=9$) in domestic houses in Bahrain with 7.8 kW – PV panels tilted at an angle 12° and nearly facing south, the equation gives the values 1043 kWh and 846 kWh, respectively, were the actual average is 1079 and 778 kWh, respectively, which is larger by 3.4% and 8.7%, respectively.

3.2 The specific yield values for the PV system

The specific yield (final yield), SY (kWh/kW_p), is usually calculated from energy output E_{AC} (daily, monthly or yearly) divided by the rated power output $P_{PV, rated}$ of the PV system [20].

The energy output, herein, is calculated as the amount of AC (alternating current) power produced by the system over a given period of time [20].

$$SY = E_{AC} / P_{PV, rated}. \quad (1)$$

3.2.1 House #1

According to the raw data provided for the monthly specific yield (in kWh/kW_p) of 7.8 kW_p – PV system for first domestic building in Bahrain (House # 1), it is found that the maximum SY obtained, in a particular day, in 2019, was 6.03 kWh/kW_p (on 23 April), followed by 5.61 kWh/kW_p (on 24 April).

Table 1 clearly shows that May and June are the months that have more SY monthly average; for example, in May, the monthly SY was 142 kWh/kW (daily = 4.6 kWh/kW) and in June it was 141 kWh/kW (daily = 4.7 kWh/kW).

Figure 14 shows the monthly average Specific Yield per day (in kWh/kW_p) of a rooftop 7.8 kW – solar PV system for House # 1) in 2019. The annual average of specific yield for this domestic building is 1407 (3.86 kWh/kW_p/day).

3.2.2 House #2

According to the raw data provided for the monthly Specific Yield (in kWh/kW_p) of 7.8 kW_p – PV system for first domestic building in Bahrain (House # 2), it is found that the maximum SY obtained, in a particular day, in 2019, was 6.03 kWh/kW_p (on 23 April), followed by 5.61 kWh/kW_p (on 24 April).

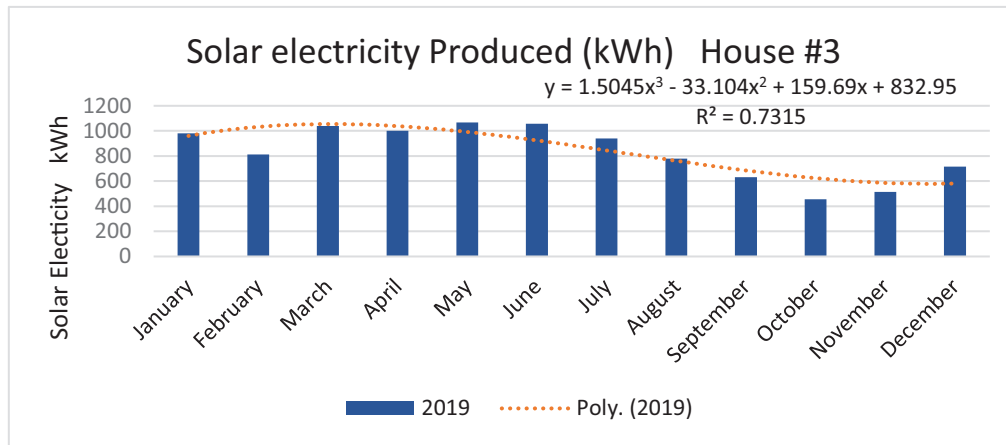


Fig. 9. The monthly solar electricity (in kWh) in 2019 produced from 7.8 kW solar PV system at rooftop for domestic building in Bahrain (House #2).

Table 3. The monthly solar electricity produced and the specific yield from 7.8 kW to solar PV system at rooftop for house #3 in Bahrain in 2019.

House # 3		
Year 2019	Solar electricity (kWh)	Specific yield (kWh/kW)
January	981.45	100.17
February	812.22	104.14
March	1040.53	133.39
April	1000.5	128.77
May	1067.78	136.82
June	1057.31	135.57
July	940.91	120.65
August	780.57	100.05
September	631.27	80.95
October	454.63	58.28
November	513.72	65.86
December	714.49	91.57
Total	9995.38	1256.22
Average	832.95	104.69

Table 2 clearly shows that May and June are the months that have more SY monthly average; for example, in May, the monthly SY was 148 kWh/kW (daily = 4.8 kWh/kW) and in June it was 146 kWh/kW (daily = 4.9 kWh/kW).

Figure 15 shows the monthly average Specific Yield per day (in kWh/kW_p) of a rooftop 7.8 kW – solar PV system for House # 2 in 2019. The annual average of specific yield for this domestic building is 1468 (4.0 kWh/kW_p/day).

3.2.3 House #3

According to the raw data provided for the monthly Specific Yield (in kWh/kW_p) of 7.8 kW_p – PV system for House # 3, it is found that the maximum SY obtained, in a

particular day, in 2019, was 6.0 kWh/kW_p (on 21 April), followed by 5.63 kWh/kW_p (on 22 April).

Table 3 clearly shows that May and June are the months that have more SY monthly average; for example, in May, the monthly SY was 137 kWh/kW (daily = 4.4 kWh/kW) and in June it was 136 kWh/kW (daily = 4.5 kWh/kW).

Figure 16 shows the monthly average Specific Yield per day (in kWh/kW_p) of a rooftop 7.8 kW – solar PV system for House # 3 in 2019. The annual average of Specific Yield for this domestic building is 1468 (4.0 kWh/kW_p/day).

3.2.4 House #4

According to the raw data provided for the monthly Specific Yield (in kWh/kW_p) of 7.8 kW_p – PV system for House #4, it is found that the maximum SY obtained, in a particular day, in 2019, was 6.1 kWh/kW_p (on 23 April), followed by 5.83 kWh/kW_p (on 24 April).

Table 4 clearly shows that May, July and June are the months that have more SY monthly average, i.e. 146 kWh/kW (daily = 4.7 kWh/kW), 145 kWh/kW (daily = 4.7 kWh/kW), and 143 kWh/kW (daily = 4.8 kWh/kW), respectively.

Figure 17 shows the monthly average Specific Yield per day (in kWh/kW_p) of a rooftop 7.8 kW – solar PV system for House # 4 in 2019. The annual average of Specific Yield for this domestic building is 1452 (4.0 kWh/kW_p/day).

Figure 18 shows the monthly average solar yield (kWh/kW/month) generated in 2019 in each of the four domestic houses in Bahrain, each having 7.8 kW – PV at roof top at tilt angle 12° but varies slightly in the azimuth angle of the PV panels. The black bar is for the average of the monthly yield of all houses.

Table 5 shows the monthly average of the specific yield in 2019 of all four domestic houses in Bahrain (right column). The average SY for all four houses is 116.3 kWh/kW/month (3.9 kWh/kW/day = 1424 kWh/kW/year). The highest monthly average is May (143.1 kWh/kW = 4.6 kWh/kW/day) and the least is in November (88 kWh/kW = 2.9 kWh/kW/day).

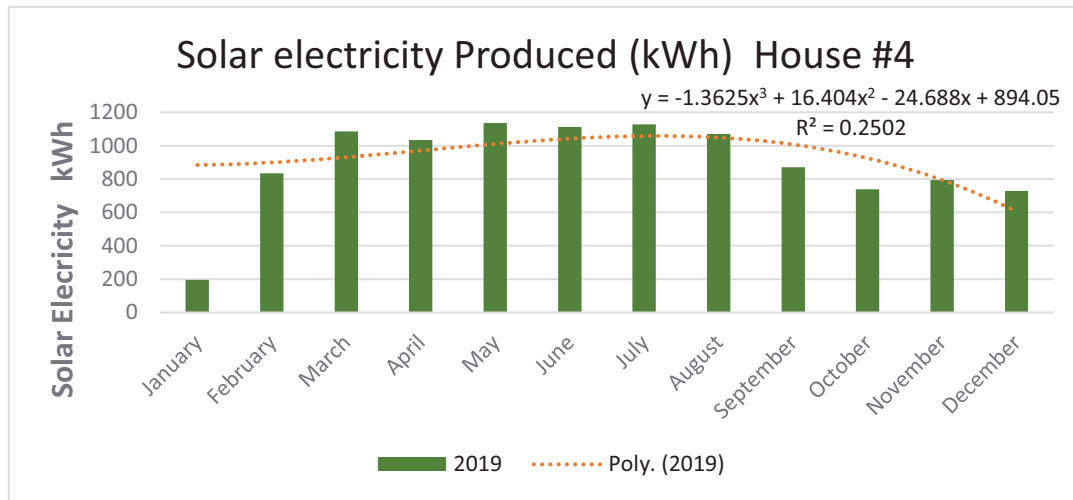


Fig. 10. The monthly solar electricity (in kWh) in 2019 produced from 7.8 kW solar PV system at rooftop for domestic building in Bahrain (House #4).

Table 4. The monthly solar electricity produced and the specific yield from 7.8 kW – solar PV system at rooftop for house #3 in Bahrain in 2019.

House # 4		
Year 2019	Solar electricity (kWh)	Specific yield (kWh/kW)
January	195.48	102
February	834.11	106.92
March	1086.02	139.22
April	1034.63	132.65
May	1135.59	145.59
June	1111.86	142.53
July	1128.12	144.65
August	1070.03	137.18
September	871.24	111.71
October	738.93	94.75
November	794.41	101.86
December	728.158	93.37
Total	10,728.58	1452.43
Ave	894.05	121.04

The following polynomial correlation is found between the specific yield (X) in particular month (Y), with relatively high correlation coefficient ($R^2=0.881$) i.e.,

$$\text{Specific yield, } Y = 0.24x^3 - 6.08x^2 + 40.36x + 60.31 \text{ (kWh/kW)}. \quad (2)$$

For example, to estimate the expected SY in March ($x=3$) and in September ($x=9$) in domestic houses in Bahrain with 7.8 kW – PV panels tilted at an angle 12° and nearly facing south, the equation gives the values of SY equal to 133.2 kWh/kW and 106 kWh/kW, respectively,

were the actual average (Tab. 5) is 138.3 kWh/kW and 99.7 kWh/kW, respectively, which is less by 3.6% and larger by 6.3%, respectively.

In comparing this value with first 8.64 kW BIPV at Sadeem building in Bapco at Awali (company building [7]), Kingdom of Bahrain, this value (4.13 kWh/kW/day) seems to be close to that reported for Bapco house which has SY ranging from 3.6 kWh/kW/day to 4.6 kWh/kW/day, i.e. with an average 4.13 kWh/kW/day.

In comparing with other Gulf Cooperation Council Countries (GCC), for a building in Abu Dhabi [21], the SY was 4.7 kWh/kW/day, on average. In the Kingdom of Saudi Arabia [22] the average SY was 4.49 kWh/kW/day. In Oman [23], the SY was 5.13 kWh/kW/day. In Qatar [24], in average, it was 5.5 kWh/kW/day.

Moreover, the annual average daily final yield of other monitored PV systems previously reported outside the GCC region includes: In Poland [20], for July and August 2021, the highest median value of SY was 5.3 kWh/kW_p and the maximum SY was 7.0 kWh/kW_p. For House 4 #108, the maximum SY per day was 6.12 kWh/kW_p – which is less than the Polish value because in their work the panels were facing south with tilt angle 20° (Poland latitude is 35° N), made of Longi Solar LR6-60HPH, efficiency 19.3%; Germany, 3.2 kWh/kW_p/day [25]; Australia (Sidney): 3.8 kWh/kW_p/day [26]; India, 3.8 kWh/kW_p/day [27]; Ireland, 2.4 kWh/kW_p/day [28]; Norway: 2.55 kWh/kW_p/day [29]; Spain: 3.8 kWh/kW_p/day [30]; Netherlands: 2.6 kWh/kW_p/day; Belgium: 2.6 kWh/kW_p/day; Luxembourg: 2.7 kWh/kW_p/day; Germany: 2.7 kWh/kW_p/day; France: 3.0 kWh/kW_p/day; Italy: 3.3 kWh/kW_p/day [31]. The annual average daily final yields of the PV systems in this study were 4.5 kWh/kW_p/day.

Other reference [32] indicate that in USA, the average output of 1MW PV installation can be calculated assuming the capacity factor of solar is 24.5%; this means that solar panels will generate 24.5% of their potential output,

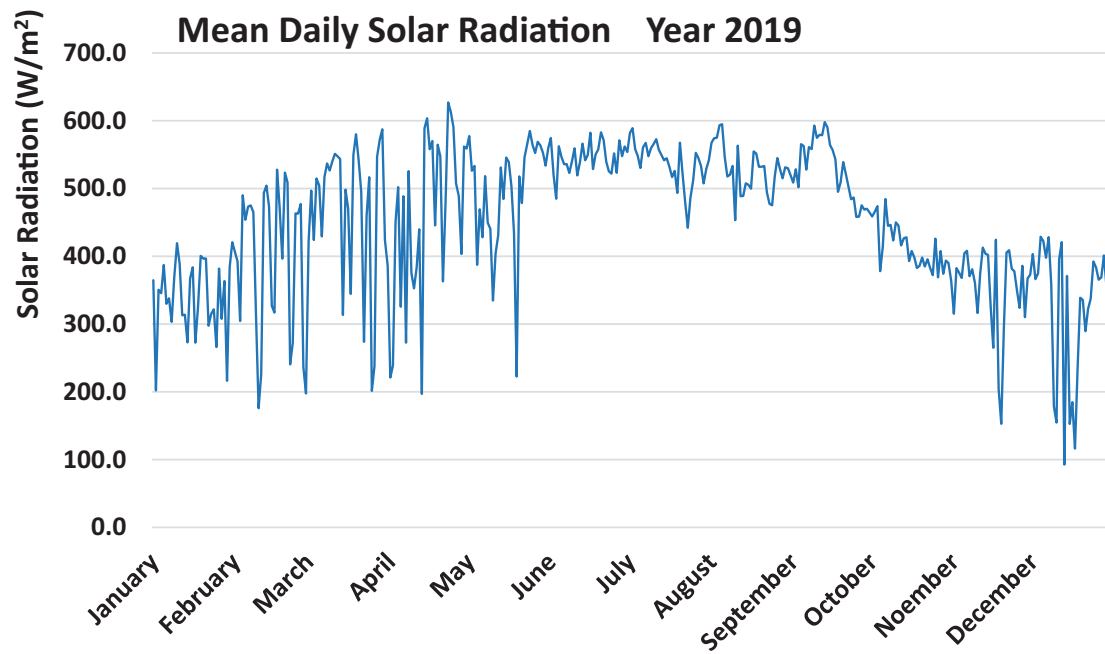


Figure 11. The mean daily solar global solar radiation (W/m^2) measured at Bahrain International Airport (Lat $26^\circ 16' \text{N}$ – Long $50^\circ 39' \text{E}$ Height 2 m). The global inclined radiation is $20,669 \text{ kWh/m}^2$ if the PV panels are tilted 12° and is $18,577 \text{ kWh/m}^2$ if the PV panels are tilted 26° .

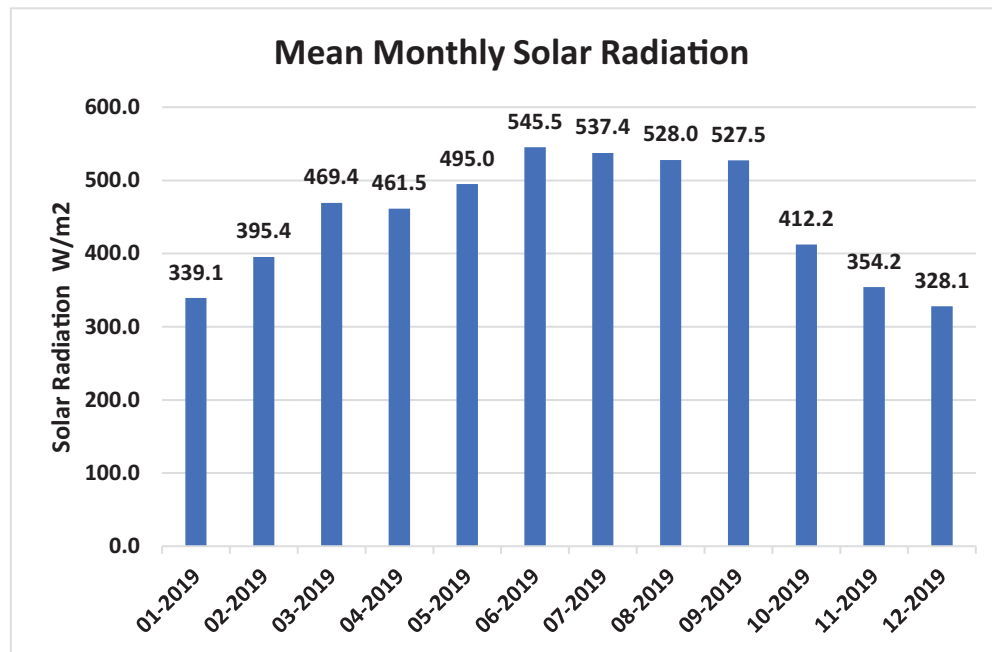


Fig. 12. The mean monthly solar global solar radiation (W/m^2) measured at Bahrain International Airport (Lat $26^\circ 16' \text{N}$ – Long $50^\circ 39' \text{E}$ Height 2 m). The total monthly solar potential in 2019 was 5393.3 W/m^2 and average monthly solar radiation was 449.4 W/m^2 . The Global inclined Radiation is 1759 kWh/m^2 if the PV panels are tilted 12° and is 1617 kWh/m^2 if the PV panels are tilted 26° .

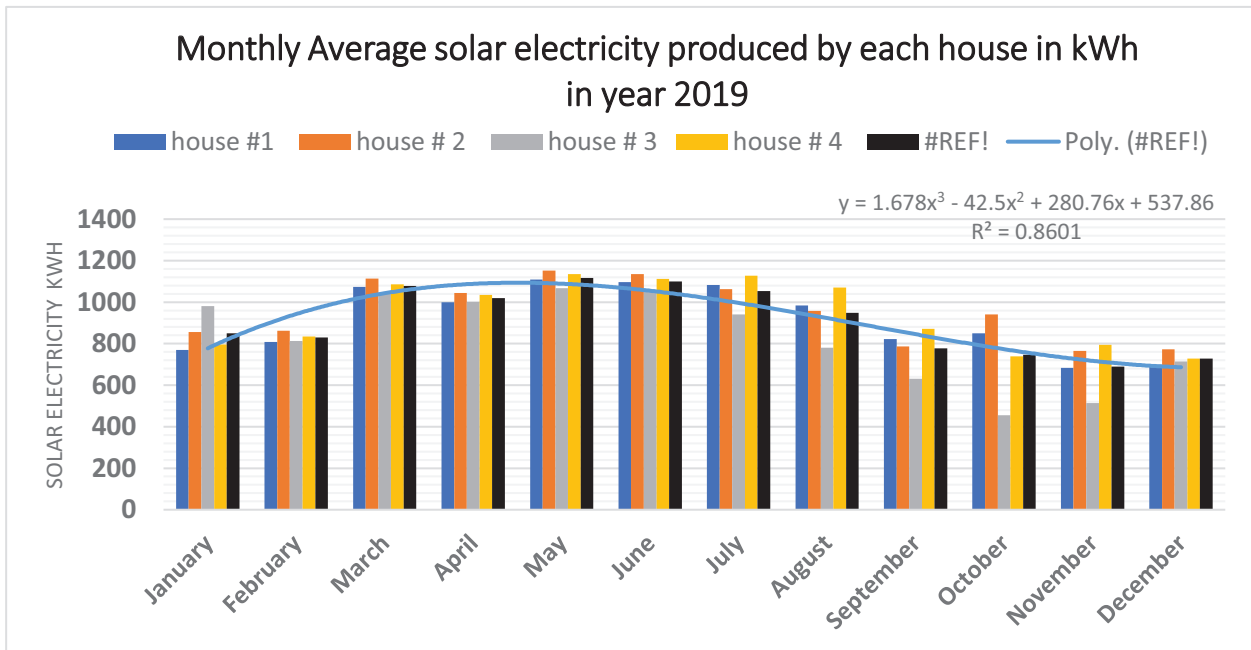


Fig. 13. The monthly average solar electricity in 2019 in four domestic houses in Bahrain, each having 7.8 kW PV at roof top at tilt angle 12° but varies slightly in the azimuth angle of the PV panels. The black bar is for the average of the monthly yield of all houses.

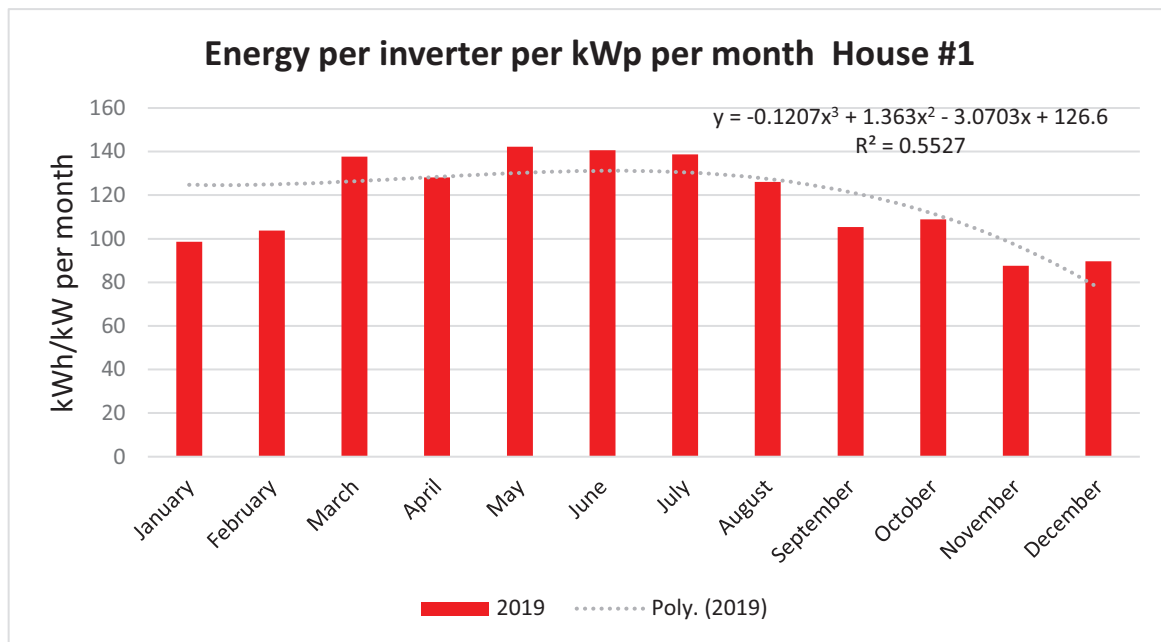


Fig. 14. The monthly average Specific Yield per day (in kWh/kW_p) of a rooftop 7.8 kW – solar PV system for the first domestic building in Bahrain (House # 1).

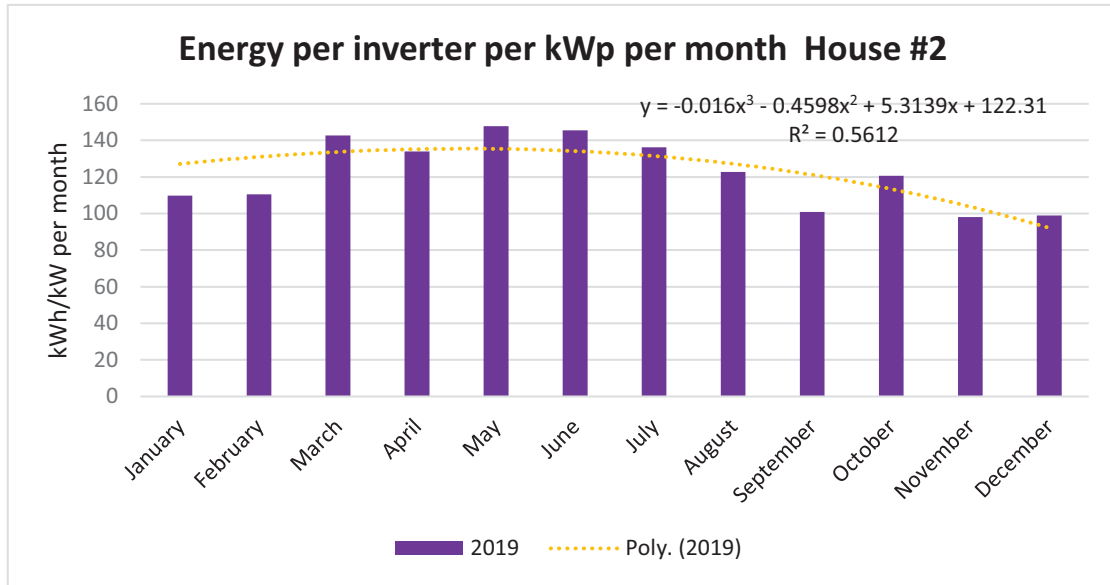


Fig. 15. The monthly average Specific Yield per day (in kWh/kW_p) of a rooftop 7.8 kW – solar PV system for the first domestic building in Bahrain (House # 2).

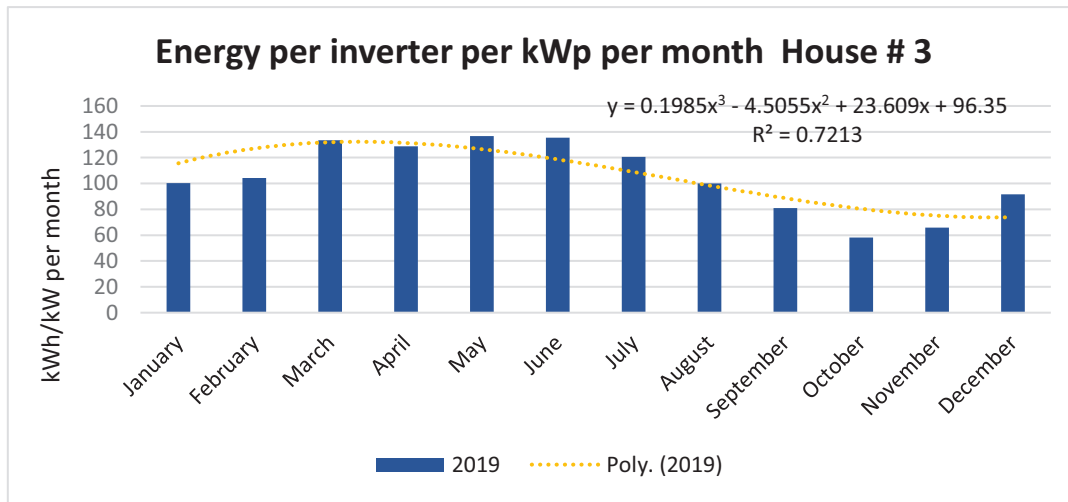


Fig. 16. The monthly average Specific Yield per day (in kWh/kW_p) of a rooftop 7.8 kW – solar PV system for the first domestic building in Bahrain (House # 3).

assuming the sun shone perfectly brightly 24 hours a day or out of 8760 h per year (365 days $\times$ 24 h) only 24% of electricity can be produced, and therefore, 1 MW of solar panels will generate 2146 MWh of solar energy per year or SY = 5.86 kWh/kW/day = 2146 MWh/MW/year). When taking into consideration the method used by Freeingenergy.com [32] then installing a 7.8 kW – PV it will produce annually 16,399 kWh (SY = 5.86 kWh/kW/day = 2139 kWh/kW/year); this much far than actually measured in Bahrain as we found that the best performance was for house # 2 which produced annual energy of 11,447.8 kWh; this is less by 30% (or equal only 0.7) of the assumed output by Freeingenergy.com. This is the significance of this work which provide developer to assume that each kW will produce annually as we are reporting herein that the average SY for all four houses is 3.9 kWh/kW/day or 1,424 kWh/kW/year instead of 2,139 kWh/kW/year.

4 The performance ration

This term complements the known terminology so called the performance ratio PR – which gives indication how efficient is the yield from the PV system. The PR per meter square is calculated using the following relation [33]:

$$PR = E_{AC}/GH \times P_{nom, PV}, \quad (3)$$

where GH is the Global inclined irradiation (kWh/m²/y) and $P_{nom, PV}$ is the PV module installed capacity (kW_p) – which 7.8 kW for all the houses. The GH (from Fig. 14) is nearly 1759 kWh/m². This is calculated using the following relation:

$$GH = \text{daily average of } G_h \times N \times 365 \times \cos\beta, \quad (4)$$

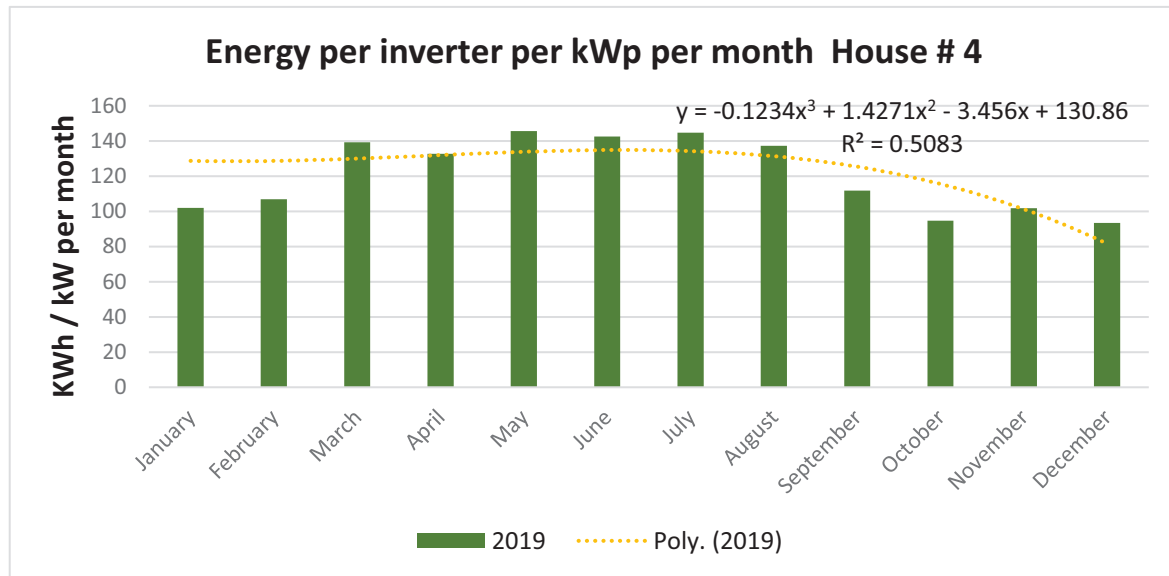


Fig. 17. The monthly average Specific Yield per day (in kWh/kW_p) of a rooftop 7.8kW – solar PV system for the first domestic building in Bahrain (House # 4).

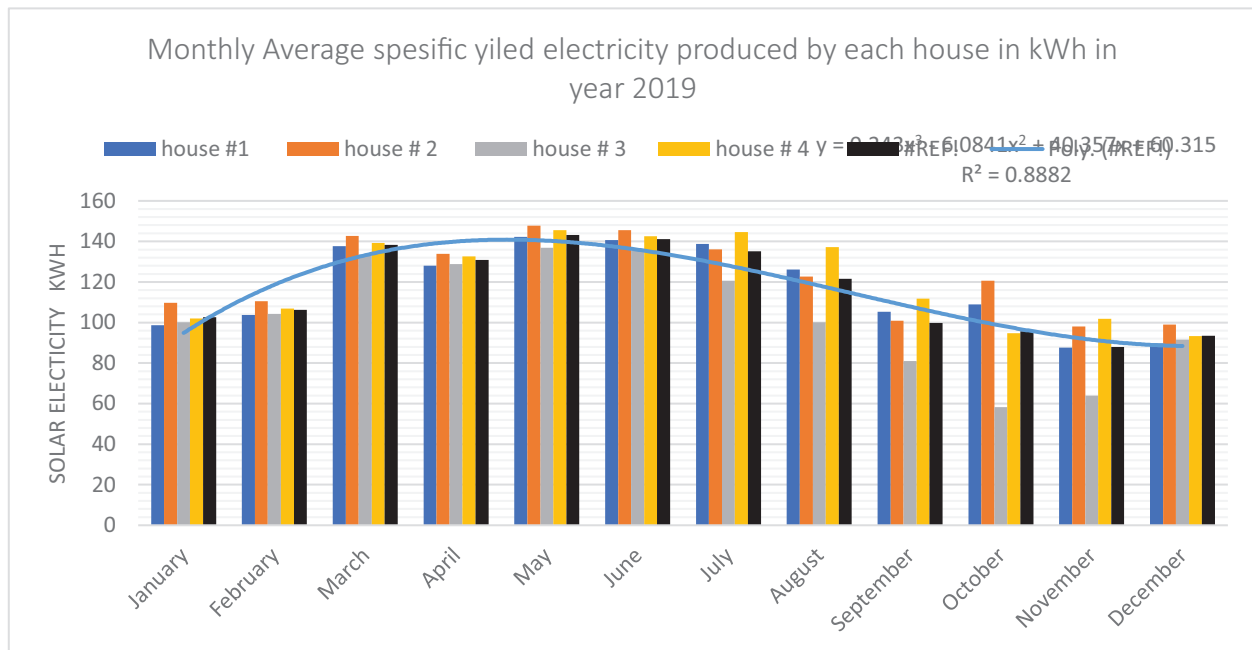


Fig 18. The monthly average Specific Yield in 2019 in each of the four domestic houses in Bahrain. The black bar is for the average of the monthly yield of all houses.

G_h is the daily average sunshine radiation on a horizontal surface, N is average daily sunshine duration (10.5h) and β is the tilt angle of the PV panels (12°). The calculation lead to a value of 1724 kWh/m^2 .

This means the average PR for house # 1 is 81.6.0% ($E_{AC}=10,978 \text{ kWh}$), for house # 2 is 85.1% ($E_{AC}=11,447.8 \text{ kWh}$), for house #3 is 74.3% ($E_{AC}=9995.4 \text{ kWh}$) and for house # 4 is 79.8% ($E_{AC}=10,728.6 \text{ kWh}$) . This makes the average PR for all four houses is 80.2%.

5 The environmental benefits

Bahrain has set a national target of achieving carbon neutrality by 2060, with an interim goal of a 30% reduction in CO₂e emissions by 2035. Among the proposed policies to achieve this target [34] is the adoption of renewable energy technologies. Luckily, solar and wind energies in specific was extensively explored on the GCC level; refer to references [35,36].

In taking into consideration the conversation from kWh solar PV to kg of CO₂ equivalent used by Cleanmax

Table 5. The monthly average solar electricity generated in 2019 of four domestic houses in Bahrain (left column) and the monthly specific yield (right column), each having 7.8 kW – PV at roof top at tilt angle 12° but varies slightly in the azimuth angle of the PV panels.

Month 2019	Solar electricity generated (kWh)	Specific yield (kWh/kW)
January	850.6	102.6
February	829.2	106.3
March	1078.6	138.3
April	1019.7	130.9
May	1116.3	143.1
June	1100.3	141.1
July	1053.5	135.1
August	947.9	121.5
September	777.6	99.7
October	746.1	95.7
November	689.1	87.9
December	728.6	93.4
Average	911.5	116.3

company which is associated with University of Dubai 1.7 MW solar PV [4], which is 0.75 kg of CO₂ equivalent emission, and knowing that a five-member household in Bahrain consumes 56,575 kWh of electricity per year [37], then each 7.8 kW – PV system installed on the rooftop (average annual solar electricity produced is will save about 19% of conventional energy consumption (natural gas) as the average of the four houses annual solar electricity generation is 10,788 kWh. This means each house will cut annually 8.0 ton of CO₂ emission. Other references [38] consider every 2435 kWh equals 1 metric ton of CO₂ emission (1 kWh = 0.41 kg of CO₂ emission) which means each house will cut annually 4.42 ton of CO₂. Also, other reference [39] considers 1 kWh is equal to 0.309 kg_e and hence, the cut in CO₂ emission from each house in Bahrain with installation of 7.8 kW will be 3.3 ton per year. In nutshell, each of these houses will cut CO₂ not less than 3.3 ton and no more than 8.0 ton annually. Furthermore, assuming that each kWh equals 3.41 ft³ natural gas [40] then each house of the four will save annually about 36800 ft³. This saving can be used for petrochemical industry instead of burning for electricity.

The initiative of the MEWA with a support from Tatweer (governmental oil and Gas Company) to financially support 10 domestic buildings to install 7.8 kW – PV (among them is these four houses (House #1 to # 4) is among the endeavors to reduce 30% CO₂e emissions in Bahrain by 2035. This means that if all houses in domestic buildings (villas) in Bahrain-which are 137,284, out of 273,733 buildings [41], is installed with 7.8 kW – PV, rooftop, and each produce annually 10,788 kWh then the cut in CO₂ will be about 11 million ton (1.11×10^{10} kg). Since in 2021, CO₂ emissions for Bahrain was 37.5 million tonnes (3.7×10^{10} kg) [42], then this PV roof – top

installation on all domestic buildings in Bahrain will represent nearly 27% cut in CO₂; which can lead to Bahrain's ambition to be zero emission by 2060 adopting a number of initiatives to become carbon neutral, including quadrupling the mangrove trees and afforestation.

CO₂e emissions in Bahrain are projected to grow continuously, therefore, if mitigation is tackled implicitly through energy efficiency and renewable energy initiatives can make 23% reduction in CO₂e emissions by 2040 [43]. Adopting additional measures is needed to achieve the recently set emission reduction target of 30% by 2035. The findings revealed potential areas for improving mitigation efforts in Bahrain. Priority areas for mitigation actions, as identified by experts, were mainly related to policy and governance. Focus needs to be paid to the social aspect of climate change mitigation. Recently [44], the effect of applying the photovoltaic panel on reducing heat input from roof to interior was studied by evaluating the air temperature, the surface temperature of the roofs, the temperature and humidity index and the radiation heat load. The results show that applying the PV panel on the roof, regardless of the type of tile of the house, is efficient in reducing the air temperature by about 0.4 °C, and the RHL about 4 W/m². This means installing rooftop solar PV in all domestic buildings in Bahrain will contribute to further CO₂ emission due to relatively lower interior temperature.

6 The pay-back period

The government had arranged with the developers that the cost of every 7.8 kW – PV, rooftop system should not exceed BD 3500—including fixing, maintenance, equipment and two years cleaning. Now, when referring to Table 5, it is clear that no more than 12,000 kWh of solar electricity can be generated from the PV's, annually. The monthly solar electricity generated 1000 kWh. This clearly understood from our finding in Section 2, Table 3, the maximum SY was 5.08 kWh/kW_p/day, which means that per month (30 days) maximum generated solar electricity is 1189 kWh. This solar electricity production will be purchased @ 3 fils/kWh since it fall in the subsidized category (0–3000 kWh), whereas from 3001 to 6000 kWh it costs 9 fils/kWh – for local first home domestic consumption. This means in a year the customer will produce 14,268 kWh which worth nearly BD 43. This means to cover a cost of BD 3500 it requires nearly 81 years. This is not encouraging for a customer wants to invest in solar energy application. Previous studies [37] suggested a purchased tariff of for each kWh of solar electricity is 75 fils/kWh (\$0.199) to 85 fils/kWh (\$0.227 per kWh). They also suggested adopting a FIT policy along with a government subsidy of 30% of the capital cost of the residential PV system. In previous paper [6], suggested that a suitable purchase for each 1 kWh solar electricity is 380 fils (about USD 1.00) for payback 5 years for the Sadeem house, Bapco (Governmental building), where the cost of the installation was relatively very high. In this study, a purchase of 100 fils (27 ¢USD) per kWh for solar electricity may be attractive for Pay-back in 3 years for domestic houses.

According to Alsabagh [45], although net metering is spread widely, it was found to be ineffective for Bahrain because the tariff for residential electricity consumption is relatively low. Net metering is more successful when the tariff is high and per-capita electricity consumption is relatively high [46].

Recently [47], in studying the feasibility of using rooftop solar PV fed to the grid for Khalifa Town houses in the Kingdom of Bahrain, it was concluded that installing 17kW – PV panels, for each of 1724 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 CO₂ emission by 34,794 tons, i.e., reducing 21 % of the town's total CO₂ 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.

With the COVID-19 pandemic, and may be similar future virus that required lock – in at houses, and subsequently domestic electricity; requires real change to conventional energy consumption pattern especially in the residential sector. A recent study in Hong Kong [48] quantified the increased energy demand during work-from-home arrangement, using high-rise public residential buildings, where its government announced work-from-home arrangement four times in 2020 which led to a 9% residential energy demand increase where photovoltaic rooftop can supplement this increased energy demand. It was shown [48] that during the four work-from-home periods, photovoltaic system could have supplemented 6.8% to 11% of the increased energy demand, mainly subject to the air-conditioning operation and solar generation.

Jaysawal et al. [49], made a literature overview on the existing Net Zero Energy Buildings (NZEB) to make them self-sustaining and net zero in order to improve energy efficiency of the buildings. They concluded that if enough renewable energy (Solar PV Rooftop installation) could be used, NZEB could potentially be achievable with power production since buildings account for a large proportion of the world's total energy and carbon emissions, and play an important role in formulating strategies for sustainable growth.

7 The owners response toward installing rooftop PV system

In order to understand the impacts of adopting rooftop solar in the United States, a polled of 1000 US homeowners to view their opinions on and overall experience with solar panels. Homeowners who have installed solar panels explained their decision toward going PV rooftop. The top reasons are [50]:

- Save the environment (60%)
- To be energy secured (54%)
- To reduce energy bill (52%)
- To reduce energy reliance (49%)
- To benefit from tax credit/rebates (37%)

- To shade roof (29%)
- To be off-grid: 28%

Homeowners who adopted solar spent \$11,735, on average, and it took seven years to see a return on investment. On the other hand, those who haven't made the switch to rooftop solar shared their top deterrents:

- Too costly (22%).
- Lack of knowledge on incentives (11%).
- Waiting on Nexfor more advanced PV and energy technology (10%).
- Credit concerns (8%).
- Lack of knowledge how PV works (6%).
- No available suitable Roof for PV installation (5%).

In an interview with the owner of the first 7.8 kW – PV domestic building in Bahrain (House 4 #108) on 30 July 2022, he had summarized the advantage and drawbacks of installing PV system on the roof. These are: Solar energy is a renewable energy source and is abundance in Bahrain. Therefore, it has to be utilized to reduce load on the national grid.

- The maintenance requirement is very low; this indicates the reliance on the component of PV installation.
- It saves the country from the background noise pollution, as gas turbines produces heat and noise.
- It has attractive looking and gives more beauty to the house.
- Family members can use the area under the installed PVs as a lounge for social gatherings.
- The roof of the house will be cooler due to shade of PV panels. The shadow forecasted on the split unit air conditioners make the conditioners performance better. Moreover, the heat from roof to rooms through the ceiling will be much less. This makes interior temperature of the house lower than usual and accordingly less electricity consumption.

The drawbacks are very little, which are:

- The PV system is very expensive.
- The regular cleaning, either once a week or twice a month or once a month.

8 Conclusion

Installing 7.8kW – PV on four domestic building in Bahrain on the rooftop PV leads to the following findings and benefits:

- The annual solar electricity yield ranges from 9995 kWh to 11,448 kWh.
- The daily average specific yield per each domestic house ranges from 3.43 kWh/kW/day to 4.02 kWh/kW/day.
- The average performance ratio (PR) of the PV system varies from 75.1% to 65.6 %.
- The lower performance of one of the houses among the other is due to a shade forecasted on the panels when the sun moves from west – south to north –south.
- If all houses in domestic buildings in Bahrain-which are 137,284 out of 273,733 buildings are installed with 7.8 kW-PV, rooftop, then the cut in CO₂ will be about 11 million ton (1.11×10^{10} kg). Since in 2021, CO₂ emissions for Bahrain was 37.5 million tonnes (3.7×10^{10} kg), this is nearly 27% cut in CO₂; which can lead to Bahrain's

ambition to be zero emission by 2060 adopting a number of initiatives to become carbon neutral, including quadrupling the mangrove trees and afforestation.

- A purchase of 100 fils (27 ¢USD) per kWh for solar electricity from the domestic building may be attractive for Pay-back period of 3 years.

Future research work will be conducted on two domestic of these 10 houses to study the performance of the PV system on rooftop by cooling the PV panel, in an innovative way, like fine gray water spray or water recirculation using part of the solar electricity produced, as this gives better PV efficiency (performance) due to heat removal from PV panels [51] and removing the dust on PV surfaces as dust reduces the efficiency of PV panel by 10% of PV by about 11% for single crystalline cells [52].

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