Cost-Efficiency Study of BIPV Systems in Qatar Residential Houses

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Abstract- Energy Consumption for the residential sector in Qatar is on the rise. This high demand of electricity in this sector is of course due to urbanization and growth in population. The objective of this study is to assess the cost effectiveness of Building Integrated Photovoltaic (BIPV) panels in residential houses in Qatar. A typical Villa-type house is assessed when BIPV is installed and the equivalent annual cost at different discount rates from 0% to 20% is calculated. The corresponding reduction of CO_2 emission at the power station is also estimated. The results are then extrapolated for all residential houses in Qatar and the total CO_2 savings are then calculated. An economic analysis is performed and the payback period (PBP) for the BIPV is calculated taking into account the initial cost and the maintenance cost. The calculations performed showed that the cost per kWh is 6.85 cents, thus the annual cost per house at 0% discount rate is around $4,193 including savings on CO_2 emissions. The PBP for the BIPV is calculated to be 34 years. The total CO_2 emissions' savings are estimated to be around 2.17 $MtCO_2$ per year which is equivalent to 65 million USD per year.

Keywords Photovoltaic, Solar energy, Qatar, Electricity, CO_2 emissions, Cost

1. Introduction

Energy demand in Qatar is on the rise due to the increase in population and urbanization. In 2008, Qatar's total primary energy consumption surpassed 1055 x10^{15} KJ for the first time, nearly double its consumption in 2001 [1]. This rapid consumption growth was driven by the rapid growth of its economy and population that almost quadrupled in 22 years [1].

The increased consumption of energy is linked to an increase in the electricity consumed where the demand for electrical power has increased many folds in the last decade going from 8 501 GWh in 2000 to about 26 377 GWh in 2010 [2]. Qatar electricity is consumed within three different sectors: domestic (residential and commercial buildings), industrial and other auxiliary use. The residential and commercial buildings contribute to 60% of the total electricity consumption [3].

The recent growth in Qatar's energy demand comes at a time of increasing global concern over carbon emissions and resulting global climate change. According to the UN online data source, Qatar is the highest carbon dioxide emitter per capita [4]. Being an energy producer country, more than 67% of total CO_2 emissions emerge from heavy-industry activities. The remaining CO_2 emissions are due to energy consumption in domestic, transport, construction and other sectors. Among these, around 55% of the emissions are due to electricity and water consumption in the residential and commercial buildings [5].

The large percentage of power consumed in buildings creates some challenges as well as opportunities. On one hand, the energy consumed in buildings will increase tremendously in the next decades but on the other hand there are a lot of solutions available today that may play a crucial role in reducing this part of electricity consumption such as building labelling program, standards and codes in buildings, and technology efficiency [6].

The opportunity of saving more energy in buildings has increased by introducing the concept of solar-based technologies such as Building Integrated Photovoltaics (BIPV). Implementing solar energy in buildings not only saves energy but also cuts down on the CO_2 emissions and therefore helps in decreasing the carbon footprint. The available global solar energy resource is 23000 TW/yr [7]. Assuming the rate of usage in 2005 remains constant globally, then running out of conventional fossil fuel will be by 2045 and coal by 2159. Less than 0.07% of available solar energy per year is sufficient to entirely replace fossil fuels and nuclear power as energy resources [7]. These numbers demonstrate that solar can be a good source of energy so the conventional sources such as fossil fuel and coal can last longer. In the next few years, the cost of fossil fuel is expected to increase and the cost of BIPV is expected to decrease since more technologies are being implemented. The global installed PV capacity reached 30 GW in 2012 and is expected to grow until 85 GW in 2017 which is enough to produce around 280 TWh of electricity in 2017 [8, 9].

Efficiency of the solar modules is increasing while manufacturing and selling prices are continuously decreasing with the development of the technology [10]. The cost has dropped by 70% during the last 10 years and it reached around 1.6 \$/W in July 2011 [11]. As the installed cost of solar PV is continuously decreasing, solar application is becoming justified to be used in building applications.

Many studies have been conducted in order to assess the economic feasibility of BIPV systems in the GCC and other countries. The cost-effectiveness for this investment can vary from one country to another depending on how much electricity household uses and the price of conventional electricity. It has been shown that adopting the PV technology in residential buildings is not cost-effective for most of the GCC countries due to the highly subsidized prices of electricity in most of these countries [12]. On one hand, in Saudi Arabia, the PV technology wasn't presented as a cost-promising alternative for electricity generation due to the current low price of energy compared to the cost of PV systems [13]. In Oman, it was found that PV energy is competitive with diesel generation only at the best location without including the externality costs of diesel [14] and would become a cost-effective solution for UAE only if PV investments are subsidized and reasonable prices for electricity tariffs are implemented [15]. On the other hand, PV systems in residential buildings appear to be a technically and economically feasible option for Kuwait [16] while it was not really recommended in Bahrain and other GCC countries [17]. An economic analysis of PV systems in Italy showed that this option is a very promising long-term investment to be adopted by Sicilian farms [18]. It is also a recommended solution to be implemented with grid-connected systems in some public locations in Southern Spain [19].

In order to increase the efficiency of BIPV systems, sunny and clear locations with higher incident solar irradiance should be chosen [20]. This key requirement for PV technology can be easily met in Qatar where the annual average solar irradiation is estimated at 2190 kWh/m^2 a year [21].

The study here will evaluate the application of solar PV in Qatar's houses taking into account its economic feasibility through the evaluation of the technology pay-back period (PBP). The proposed study will be conducted for one typical villa in Qatar taken into consideration the initial cost, maintenance cost, and execution cost. The result then will be projected to all houses-villas in Qatar and the savings in CO_2 emissions will be also quantified. This study is important given the fact that very few similar assessments have been done so far in Qatar and many other countries in the region.

2. Data and Methods

2.1. General Data about Qatar

Qatar is a desert country with a clean, hot, and dry atmospheric climate. Based on the NASA clearness index the average yearly reading for 20 years of Qatar is 0.66 KT which is considered nearly clear sky all year long. For values above 0.5 KT, the location is considered to have a clear sky on most days of the year [22]. The geographic coordinates for Qatar are 25°18′N of latitude and 51°30′E of longitude [21, 23]. The maximum yearly total global solar radiation corresponds to a tilt angle of 25˚ which is equal to Qatar's latitude. So the PV panels should be tilted at a 25˚ angle facing south. The maximum annual sun hours for Qatar is 11.6 hours daily, with an average value of 9.5 peak hours per day as can be seen from Fig. 1. The average daily solar radiation is 5.1 kW/m^2 [24].

The average roof area (ARA) of a typical residential villa in Qatar is assumed to be 326 m^2, where in most houses the roof areas are flat and in some houses the roofs consist of central air conditioner units. Therefore this area is almost empty and it can be used for PV installation. Surfaces of the roof area are built of reinforced concrete, which can absorb the high loads and additional weights unlike houses built of wood and other materials which do not have the capability to accommodate additional loads, and the flat surfaces are compatible with any direction of solar panels (Table 1).

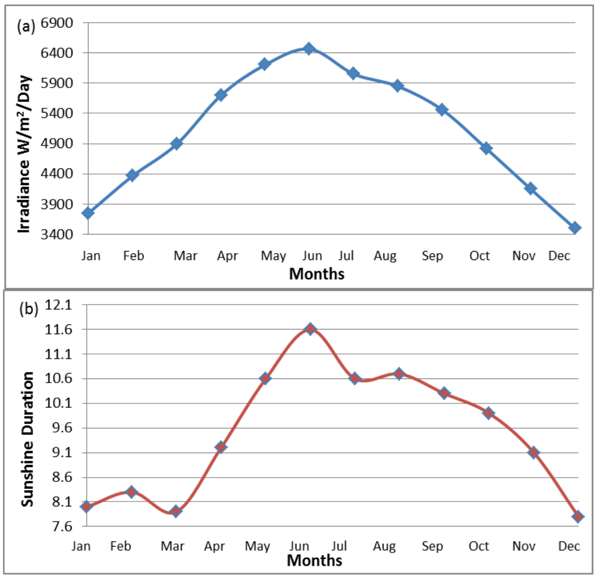

Fig. 1. Monthly distributions of solar radiation (a) and sunshine solar hour (b) in Qatar [24]

Table 1. Description of the prototype residential villa

Description	
No. of floors	2
Average Roof Area	326 m^2
Roof construction	Reinforced concrete
Average family members	6
Average Electricity consumption	135 000 kWh/yr
Number of occupied villas in 2010	50 380

The domestic consumption of electricity in Qatar in 2010 was 16,843,614 MWh/yr [25]. An average consumption is calculated to be around 135,000 kWh/yr assuming that the total number of residential units connected to the electricity grid in 2010 is 124,665 [26]. The number of occupied villas in Qatar for 2010 is about 50,380 villas [26]. An estimate of 50,000 villas is taken here for the calculations. All the findings are done per house therefore the uncertainty in the total number of villas will not affect to results.

2.2. Components used in BIPV systems

A complete BIPV system constitutes of many components; PV modules, charge controller to regulate the power, power inverter, appropriate support and mounting hardware, wiring, and safety disconnected fuse boxes [27]. The PV modules or solar panels can be used as a component of a larger photovoltaic system to generate and supply electricity in commercial and residential applications. The three main fixed types of solar cells (module) commonly used are the thin film layers or amorphous, the mono-crystalline-crystalline, and the poly-crystalline. Table 2 presents the selection of the most suitable one to the designed location requirements in terms of technical capabilities. For instance, when the size of land required is limited, mono- or poly-crystalline are the best choices. The amorphous can be used if no limitation on the area is addressed since it is cheaper than the other two but it occupies almost double the area the other two types occupy [20].

Table 2. Properties of the PV systems [20]

Cell type	Cell eff. (%)	Module eff. (%)	Active Surface (m^2/kWp)	Weight (kg/m^2)
Amorphous TF- CdTe	7.6	7.1	14.1	19.0
Mono c-Si	15.3	14.0	7.1	14.6
Poly c-Si	14.4	13.2	7.6	14.6

The use of solar PV system and advanced solar cell are based upon life cycle, efficiency, and cost assessment of the PV. Selecting the right module to do the work depends on a number of factors: A module with maximum efficiency, occupying minimal area with the highest output power and lowest initial cost, is selected. Table 3 compares the specification data of four modules' types along with their prices: Samsung, DMSOLAR, SinoSolar and BestSun. The cells efficiency are about 15% for all types, however the price per watt vary from \$1.55/watt to about \$2.41/watt [28, 29, 30, 31, 32].

In this study Poly-crystalline PV modules are used in the analysis since they will be installed at the rooftop of a typical Qatari Villa where the area is obviously limited and thus, a maximum system output power is required. Module model BestSun156 P300-72 shown in Table 3 is the most convenient module and will be the selected sample, due to a number of reasons:

1. The price of the peak wattage is the lowest of the four models, \$1.55 per watt as shown in Table 3.

2. The module has the highest efficiency at 15.5%.

3. It is a poly-crystalline module with the highest peak wattage (300 W).

An average roof area for a Qatari villa is 326m^2 and each module occupies 2.2 m^2 including the shading area. This means that the number of modules per PV system is as follows = total roof area / area of a single module= 326 m^2 / 2.2m^2 = 148 modules per house. The module has a 5-year product warranty and 25-year guarantee for 80% of the module total output efficiency. The warranty is included in the initial cost prices [28].

The Balance of the System (BOS) of a PV consists of all the technical and engineering parts. It mainly consists of an inverter to transform the direct current (DC) power from the PV array into a form of alternating current (AC) electricity that can combined with, and connected to, the electric utility grid. It also involves the engineering overhead, labor cost, shipping, transportation, inventory, installation, mounting brackets, cable connectors, and other miscellaneous. The BOS accounts for 30% to 40% of the cost of the PV system. In some studies, 35% is chosen as the average BOS cost of the PV.

Electricity supplied to Qatar residential houses is 3-phase which is needed to operate many appliances such as air conditioner, water boilers, elevators, etc. This requires the installation of a single 40kW 3-phase universal inverter. The cost of the inverter is \$8,810, with the manufacturer warranty of 20 years equal to the life span of the PV system [33]. In most cases, the cost of inverter which is the second highest valued part of the entire system is added to the module cost, in return decreasing the BOS cost from 35% to almost 25% [34, 35]. Other factor that influences high margin of the BOS is the labor hourly payment wage. This cost is relatively low in Qatar compared to some countries where labor cost is very high, especially for newly adopted technology, and the BOS cost can reach as high as 39% [36].

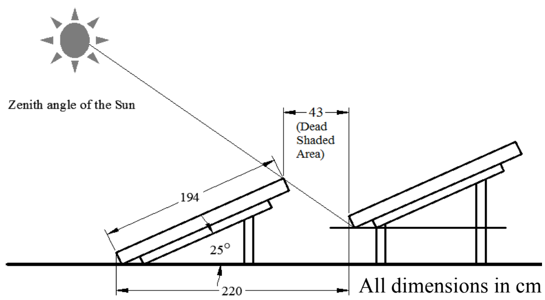

Fig. 2. The total area each module occupies

Table 3. Comparison of four different modules

Features	Samsung LPC 241 SM	Dm Solar DM 280M 2-3	Sino Solar SA260-96	Best Sun 156P 300-72
Cell Type	Mono-Crystalline	Poly-Crystalline	Mono-Crystalline	Poly-Crystalline
Efficiency	15.06%	14.4 %	N/A	15.5 %
Module Output Wattage	241	280	260	300
Module Price ($)	582	518	429	465
Price/Watt ($)	2.41	1.85	1.65	1.55
NOCT	46±2ºC	47±2 ºC	N/A	46±2 ºC
Weight (Kg)	18.6	23.2	N/A	13
Temp. Cycling	-40 to +85 ºC	-40 to + 90 ºC	N/A	-40 TO + 85ºC
Roof Area (m^2)	326	326	326	326
Area per Module (m^2)	1.6	1.95	1.66	1.95
Area Module + Shade (m^2)	1.8	2.2	1.8	2.2
Number of Modules	181	148	181	148
System Total Power (W)	43621	41440	47060	44400
Cost of Modules ($)	105342	76664	77649	68820

As mentioned previously, the PV arrays used in this work are assumed to have the same orientation as Qatar's latitude i.e. 25° angle facing south as shown in Fig. 2. Therefore, an area of 2.2 m^2 for each module was calculated based on optimizing the sun irradiation on the PV for the location of Qatar making sure that this distance will reveal the maximum output of the PV throughout the day. Thus with simple geometric formulas, the dead shaded area between the panels is calculated to be 43 cm. Each panel contains 14 modules, thus the total area needed to build the system is 326 m^2. Of course the increase of sunshine hours at the location of a PV system can lower the cost of the total system.

3. Calculations and Results

The economic assessment of the feasibility of BIPV systems in Qatar along with the calculations of pay-back period and savings in CO_2 emissions are discussed in this section. The calculations have been performed using an extensive formulation process as shown in Fig. 3

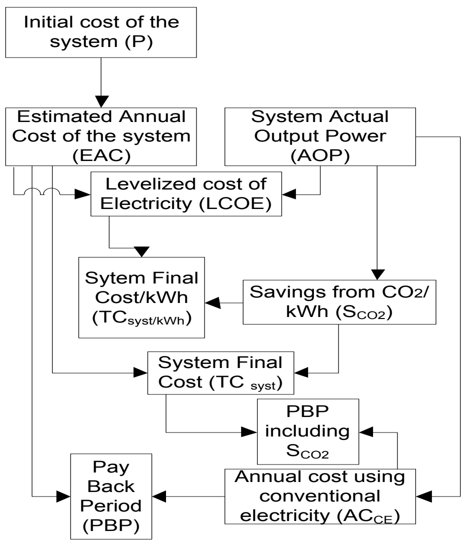

Fig. 3. Flowchart showing the formulation process used for the calculations

3.1. *Components used in BIPV systems*

As shown previously, the average annual energy consumption of a residential unit in Qatar is 135.0 MWh/yr. The average roof top area of standard Qatari house is about 326 m^2 and the total number of modules on the rooftop of a typical villa is 148 modules /system per house.

The initial cost of the system will include: the initial cost of the modules, the initial cost of the inverter, and the initial cost of the balance of the system (BOS).

The initial cost of each PV is $465. Therefore, the total initial cost of all modules (IC_{MT}) is:

$$IC_{MT} = M \times IC_M = 148 \times \$465 = \$68,820 / PVsyst.House \quad (1)$$

The inverter works with high efficiency of 96.4% and the initial cost of the inverter (*ICi*) is $8,810/system [33].

The BOS initial cost (ICBOS) of the PV system, as discussed earlier, accounts for 25 % of the system cost and this number was verified by many other researchers such as Rigter et al. [37].

Let x be the initial cost of the system, then:

$$x = 68,820 + 8,810 + 0.25x$$

Thus

$$x = \frac{\$77,630}{0.75} = \$103,506 \quad (2)$$

Thus the BOS initial cost will be:

$$IC_{BOS} = 103,506 \times 0.25 = \$25,876 \text{ per house} \quad (3)$$

So the initial cost of installing the system for a typical villa in Qatar will be:

$$P = \$103,506$$

<u>Equivalent Annual Cost (*EAC*) of the PV system</u>

The Equivalent Annual Cost (*EAC*) of the PV system is:

$$EAC = A_i + AAOM \tag{4}$$

Where *Ai* is the initial cost of the system at a certain discount rate (i), and *AAOM* is the Average Annual cost for Operation and Maintenance.

Ai is derived from the following equation:

$$A_i = P \times CRF \tag{5}$$

Where *P* is the system initial cost and *CRF* is the capital recovery factor and is calculated as follows:

$$CRF = \left[\frac{i \times (1+i)^n}{(1+i)^n - 1}\right] \tag{6}$$

With *i* the discount rate and *n* is the system useful life, assumed to be 20 years.

AAOM is estimated following the equation below [38]:

$$AAOM = \left[OM \times (1+f)\mathrm{n}\right] / n \tag{7}$$

Where *OM* is the present operation and maintenance cost estimated at 6% of the initial cost [12]: $= (P \times 0.06)/20 = \$310.5/yr$

, *f* in the annual inflation rate expected = 3.25% [39], and *n* is the system estimated useful life, equal to 20 years.

Therefore:

$$AAOM = \$320/\mathrm{yr}$$

If we assume that the lifetime of the system is about 20 years and no interest is taken into consideration, the PV System Initial Annual Cost will be:

$$P_{yr} = P / lifetime_{syst.} = \$103{,}506/20 = \$5{,}175/house \tag{8}$$

Adding to this the Operation and Maintenance costs, the Equivalent Annual Cost for the BIPV system will be \$5,495/year per house. This value is obtained at 0% discount rate. The higher discount rate values are considered, the higher will be the EAC per year as shown in Table 4.

System Annual Output Power (AOP) and Cost per kWh

To determine the actual annual output power (*AOP*) produced by the BIPV system, the ideal system output power per hour must be first determined, followed by the actual output power per hour, and finally the annual output power.

The selected module model BestSun156P300-72 is assumed to be used in this research. The total ideal output power of the system can be determined by multiplying the peak output power of each module (*MOP*) by the number of modules, where, the average roof area of the Qatari houses can accommodate 148 modules per house. The ideal peak load power (*IP*) value is:

$$IP = MOP \times M = 300W_P \times 148 = 44{,}400W_P / Syst. \tag{9}$$

The actual output power is however less than the ideal one due to some losses in the PV system, wiring and connectors, and of course the inverter.

According to Boonmee, et al. [40], the efficiency of a PV array in the PV-grid-connected system is close to the efficiency of a PV array of using standard technical data of the manual. It is indicated that the result of measuring parameters is responsible and corrective. Since Qatar climate is hot, the module efficiency is assumed to be 5% lower than the standard operating condition [6]. So the efficiency (*EM*) is taken to be instead of 15.5 % as 10.5 % on average where the loss in efficiency is mainly due to the temperature increases in the hot climate weather of Qatar.

The losses in the connections, cables, and combiner boxes amount to 5%. According to Endecon [41], power is lost due to resistance in the system wiring and connectors. Those losses should be kept to a minimal level by using the shortest wiring paths and minimizing the wire connection. So the efficiency of the wiring (Ew) is taken to be 95 %.

In many references, the efficiency value of the inverter (*Ei*) has been stated to be 96.4% [33, 42].

So the actual output power (AOP) for the system in place will be:

AOP in Qatar = average insolation /m^2/yr * module efficiency * modules area (10)

The average annual solar insolation for Qatar is 2,190 kWh/m^2/yr [21]. The module efficiency is 10.5% [28]. The area occupied by 148 modules is:

148 * 1.94 m^2 (Table 3) = 287.12 m^2

AOP in Qatar = 2,190 kWh/m^2/year * 0.105 * 0.95 *0.964* 287.12 m^2 = 60,464.08 kWh/yr.

After determining the equivalent annual cost (EAC) of the system for the newly constructed house and the system average annual output, the levelized cost of electricity (LCOE) at 0% discount rate can then be achieved as follows [43]:

$$LCOE = \frac{EAC}{AOP} = \frac{\$5{,}495}{60{,}464.08} = \$0.09/kWh \tag{11}$$

Table 4. Equivalent Annual Cost of BIPV at different discount rates

Discount Rate	Initial Cost (\$)	The Capital Recovery Factor CRF	Initial Cost/year (\$)	OM/year (\$)	System EAC	
					(\$)	(QR)
0%	103,506	0.05	5,175.3	320	5,495.3	20,057.8
5%	103,506	0.0802	8,301.1	320	8,621.1	31,467.1
10%	103,506	0.1175	12,161.9	320	12,481.9	45,558.9
15%	103,506	0.1598	16,540.2	320	16,860.2	61,539.7
20%	103,506	0.2054	21,260.1	320	21,580.1	78,767.3

This levelized cost of electricity of the system is calculated assuming no interest and the money are available upfront for the investment.

The cost per kWh for the BIPV system at different discount rates is given in Table 5.

3.2. The savings in CO_2/kWh

According to [44], a kWh of electricity produced by a conventional system will emit into the atmosphere an amount of 0.718 kg of CO_2/kWh. So the saving in CO_2 emissions (CO_{2T}) for the total amount of electricity produced is:

$$CO_{2_T} = AOP \times CO_{2/\mathrm{kWh}} = 60,464.08 \times 0.718 = 43.4tCO_2 / yr.house \quad (12)$$

Many papers estimated the cost of the damages caused by carbon dioxide emissions. The direct and indirect effects on both human health and natural biology is too uncertain to draw conclusions on the actual cost of damage; nonetheless, the average cost of carbon dioxide emissions that emerges from most studies is $30/ton [45, 46, 47]. So the money saved from reduced CO_2 emissions (S_{CO2}) will be as follow:

$$S_{CO_2} = 43.4t \times \$30 = \$1,302 / house \quad (13)$$

The saving from CO_2 per kWh ($S_{CO2/kWh}$) using solar energy will be:

$$S_{CO_2/kWh} = \$1,302 / 60,464.08kWh = \$0.0215 / kWh \quad (14)$$

The system final cost/kWh ($TC_{syst/kWh}$) at 0% discount rate will be:

$$TC_{syst/kWh} = LCOE_{kWh} - S_{CO2/\mathrm{kWh}} = \$0.09 / kWh - 0.0215 / kWh = \$0.0685 / kWh \quad (15)$$

Thus, the system final cost at the *AAOP* would be:

$$TC_{syst} = EAC - S_{CO2} = \$5,495 - \$1,302 = \$4,193 \quad (16)$$

The actual cost of conventional electricity (*CCE*) is composed of many complementary costs, like the cost of the land the power plant is built on, the cost of the fossil fuel it consumes, the annual repairing and maintenance cost, the distributing cable lines and networks. In Qatar the cost of electricity produced by conventional system (*CCE/kWh*) is almost $0.0537 /kWh [48].

3.3. Cost Differences between the PV System and CE/kWh

The final and most important result that can make a difference both to the consumer and the decision makers is the cost difference between the BIPV system and the conventional electricity. Therefore, assuming that the total annual output power of PV system was generated by conventional electricity, the total annual cost would be:

$$AC_{CE} = C_{CE/\mathrm{kWh}} \times AOP = \$0.0537 / \mathrm{kWh} \times 60,464.08\,\mathrm{kWh} = \$3,247 \quad (17)$$

Hence, the annual saving (*AS*) per house using PV system to generate electricity at 0% discount rate, and taking into account the savings in CO_2 emissions is:

$$AS = AC_{CE} - EAC + S_{CO2} = \$3,247 - \$5,495 + \$1,302 = \$-946 / \mathrm{yr} \quad (18)$$

The total annual saving per house is negative, therefore, the BIPV system costs $946 per house per year more than the electricity generated by conventional power plants. The total annual extra cost of BIPV systems for 50000 houses in Qatar (AC_{Qatar}) is:

$$AC_{Qatar} = 50,000 \times \$946 = \$47,300,000 \quad (19)$$

Excluding the saving in CO_2, the total cost for 50,000 houses in Qatar (AC'_{Qatar}) would be:

$$AC'_{Qatar} = 50,000 \times |AS - S_{CO2}| = 50,000 \times |\$-946 - \$1,302| = \$112,400,000 \quad (20)$$

The total amount of CO_2 emissions saved by 50,000 houses per year is therefore:

$$CO_{2T} * 50,000 = 43.4\ t_{CO2} * 50,000 = 2.17\ Mt_{CO2} / yr \quad (21)$$

The cost of CO_2 emissions saved is:

$$2.17\ Mt_{CO2} / yr \times \$30 / t_{CO2} = \$65.1 \times 10^6 \quad (22)$$

The above calculations show that the total annual extra cost of BIPV systems as compared to conventional electricity cost will be much less if one considers the amount of money saved from CO_2 emissions. This factor is very important from an environmental and sustainability point of view and should not be underestimated especially in a fast growing carbon-based economy such as Qatar. It should be mentioned that the cost of implementation of new power stations running on natural gas will be very close to the BIPV technology cost i.e. $0.066/kWh [49] but will certainly have many drawbacks as related to the environment.

3.4. System Pay-Back Period (PBP)

The system pay-back period is equivalent to the EAC of PV system or the final cost of the system *TCsyst* (which includes savings from CO_2) divided by the annual cost of AOP using conventional electricity, thus:

Table 5. AOP and Cost per kilowatt-hour at different discount rates in US dollars and Qatari Riyals

Discount Rate	System EAC		System AOP (kWh/house)	Cost/kWh	
	($)	(QR)		($)	(QR)
0%	5,495.3	20,057.8	60,464.08	0.09	0.33
5%	8,621.1	31,467.1	60,464.08	0.14	0.52
10%	12,481.9	45,558.9	60,464.08	0.21	0.75
15%	16,860.2	61,539.7	60,464.08	0.28	1.01
20%	21,580.1	78,767.3	60,464.08	0.35	1.30

$$PBP = EAC \times n / AC_{CE} = \$109,906 / \$3,247 = 34 yrs \qquad (23)$$

The PBP calculated for BIPV system in Qatar excluding savings from CO_2 is 34 years at 0% discount rate and 53 years at 5% discount rate (Fig. 4). It is reduced to 28 years at 0% discount rate if savings from CO_2 (S_{CO2}) are accounted. These values are longer than the PV system lifetime (20 years) which indicates that the BIPV technology is not yet efficient for use in Qatar. Our result is in good agreement with previous studies that reported a very low cost-efficiency of PV systems in Qatar [48] and long pay-back periods of 50 years at 5% discount rate [6, 12]. However, our calculation above is based on the generation cost of conventional electricity of \$0.0537/ kWh as reported in [48], which could be very low as compared to the actual generation costs. Due to the lack of information related to the real generation cost of conventional electricity in Qatar, we assume that if the cost is very close to the generation costs in Saudi Arabia or in Kuwait [12], therefore the PBP will drop to lower values as reported in Table 6.

Although the pay-back period sounds to be long, one should look at the advantages of installing PV systems in terms of CO_2 savings during this period of time. Therefore, the total amount of CO_2 saved per 50,000 houses during the PBP would be:

$$CO_{2_{PBP}} = 2.17 Mt_{CO_2/yr} \times 34 yrs = 73.8 Mt_{CO_2} \qquad (24)$$

This amount of CO_2 emissions saved during 34 years would be equivalent the amount of CO_2 emitted by the whole country over a complete year [50]. Thus, the number obtained is significant and should be taken seriously into consideration especially that the savings in CO_2 emissions can highly increase if one considers all types of residential and commercial buildings in Qatar to be equipped with PV systems for electricity generation.

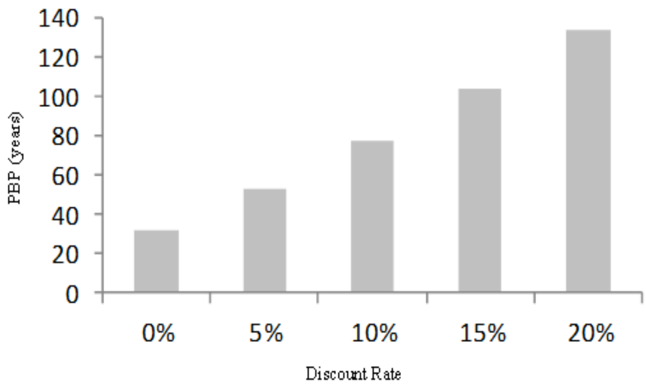

Fig. 4. Estimated *PBP* at different discount rates

Table 6. PBP comparison using conventional generation costs in Saudi Arabia and Kuwait

Country	Generation Cost (\$/kWh)	Annual Cost AC_{CE} (\$)	Annual Saving *AS (\$)*	*PBP* (yr)
Qatar	0.0537	3,247	-946	34
Saudi Arabia	0.099	5,986	1793	17
Kuwait	0.12	7,256	3063	14

4. Conclusion

We have shown in this study that electricity generated using BIPV system installed on a rooftop of a residential villa in Qatar costs around 6.85 cents per kWh which is slightly higher than the cost of conventional electricity estimated at 5.37 cents. The total cost of the BIPV system is \$ 4,193/house per year which is 946\$ higher than the cost paid for conventional electricity generation including savings on CO_2 emissions. Annual savings of \$1,793 and \$3,063 can be achieved if conventional electricity costs similar to Saudi Arabia and Kuwait are considered. The pay-back period of the BIPV systems can reach 34 years at 0% discount rate. Although this looks to be a long period, the amount of CO_2 emissions saved during these years can reach 74 million tons and will increase intensely if all residential and commercial buildings will be considered for BIPV system implementation.

The implementation of BIPV systems in Qatar residential houses might not look cost-efficient with the current electricity prices, which does not allow high monetary savings but the implementation of such technology will have many benefits for the country:

- It will set Qatar among the pioneers within the oil and natural gas exporting countries in utilizing renewable solar energy for domestic consumption and exporting the saved products to the international markets.
- It will mitigate the image of Qatar as having excessive and irrational consumption of fossil fuel and will improve Qatar's global image as one of the highest CO_2 emitter per capita. The total savings on CO_2 emissions of the country per year can reach 2.2 $MtCO_2$ equivalent to 65 million USD per year.
- It will decrease the country's dependence on fossil fuel to produce electricity and will cut on the cost of establishing new central power stations with all the transmission and distribution (T&D) facilities.

Incentives should be given and policy instruments should also be implemented in order to support the deployment of renewable energy resources in the long term. These can be in the form of environmental taxes, emission permits for producing electricity using conventional resources and removal of subsidies given to fossil fuel generation. Support policy incentives can be investment-focused where subsidies on renewable energy projects are given based on installed capacity, and generation-focused where support is given based on energy produced and sold.

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Abbreviations

Ai	Initial Cost of the system at certain discount rate i
AAOM	Average Annual cost for Operation and Maintenance
AC	Alternating Current
ACCE	Total annual cost assuming that the total annual output power of PV system was generated by conventional electricity
AC_{Qatar}	Total Annual extra Cost of BIPV systems for 50000 houses in Qatar
AC'_{Qatar}	Total Annual extra Cost of BIPV systems for 50000 houses in Qatar excluding CO_2 savings
AOP	Actual Annual Output Power
ARA	Average Roof Area
AS	Annual Savings
BIPV	Building Integrated Photovoltaics
BOS	Balance of the System
CCE	Cost of conventional electricity
CCE/kWh	Cost per kilowatt-hour of electricity produced by conventional system
CO_{2T}	Saving in CO_2 emissions for the total amount of electricity produced
CRF	Capital Recovery Factor
DC	Direct Current
EAC	Equivalent Annual Cost
EM	Module Efficiency
Ei	Inverter Efficiency
IC_{BOS}	Initial Cost of Balance of System
IC_{MT}	Total Initial Cost of Modules
ICi	Initial Cost of the Inverter
IP	Ideal Peak Load Power
LCOE	Levelized Cost of Electricity
MOP	Module Output Power
OM	Operation and Maintenance cost
P	System Initial Cost
Pyr	System Initial Annual Cost
PBP	Pay-Back Period
PV	Photovoltaic
S_{CO2}	Money saved from reduced CO_2 emissions
$S_{CO2/kWh}$	Money saved from reduced CO_2 emissions per kilowatt-hour
TC_{syst}	System final Cost
$TC_{syst/kWh}$	System final Cost/kWh