International Journal of Sustainable Energy Planning and Management Vol. 50 2026 38–54

International Journal of
Sustainable Energy Planning and Management

A Multi-Stage Framework for Developing a Virtual Power Plant (VPP) Model for Off-Site Solar Deployment: A Case Study of Bahrain

Yusuf Almoadhen[a], Rajamohamed Sumsudeen[a], Abdulla Alabbasi[b*], Abdel Rahman Musleh[a]

[a]*Electrical and Electronics Engineering Department, University of Bahrain, 1017 Road 5418, Zallaq 1054, Bahrain*
[b]*Bahrain Center for Strategic, International and Energy Studies (Derasat), Building 355, Road 96, Awali, Bahrain*

ABSTRACT

As Gulf Cooperation Council (GCC) countries accelerate their energy transitions, they encounter a shared strategic challenge: how to harness abundant solar resources within densely populated urban centers where land availability for utility-scale projects is increasingly constrained. The novelty of this work is to propose a framework that enables the integration of Virtual Power Plants (VPPs) in a regulated electricity market like the one in Bahrain, addressing a critical gap for land-constrained countries. The study employs a multi-stage framework integrating geospatial analysis via GIS for site selection, technical simulation using PVsyst modeling for 0.5 MW, 1 MW, and 1.5 MW systems, and financial evaluation across three pricing mechanisms net metering, Power Purchase Agreements (PPA), and Virtual Power Purchase Agreements (VPPA) incorporating subsidized tariff structures starting as low as 3 fils/kWh (0.79 USD cents/kWh), and economy-of-scale effects. The findings reveal that net metering delivers the highest investor returns (NPV up to BHD 370k or USD 981k) and shortest payback periods (as low as 6.8 years), but its reliance on physical grid connections and the disincentive created by subsidized tariffs limit its scalability to only those with rooftop access. PPA offers revenue certainty but caps profitability (NPV up to BHD 142k approximately equivalent to USD 376.5k), leaving consumers without electricity bill discounts. The VPPA model emerges as the most balanced mechanism, delivering investor returns at least 40% higher than PPA where NPV can reach BHD 242k (USD 641.1k), enabling annual consumer savings up to BHD 23k (approximately USD 61k) that can be for a single or group of consumers, far exceeding the BHD 550 (USD 1457) maximum under net metering and allowing regulators to recover grid costs through transaction fees while maintaining dispatch coordination. Annual CO_2 mitigation ranges from 426 to 1,278 tons depending on system size. These findings carry immediate implications for GCC policymakers: transitioning toward a digitally enabled VPPA framework can unlock private investment, broaden citizen and commercial participation regardless of location, overcome land-use constraints, and accelerate progress toward national net-zero target.

Keywords

Virtual Power Plant;
Photovoltaic;
Net metering;
Power Purchase Agreement;
Virtual Power Purchase Agreement;
Levelized Cost of Energy

http://doi.org/10.54337/ijsepm.10962

1 Introduction

The global shift toward renewable energy has accelerated the adoption of solar photovoltaics (PV), supported by improved scalability, falling costs, and high solar potential, particularly in sunbelt regions with strong irradiance levels. In 2024, global investment in solar PV increased by 20.5% to USD 514 billion, enabling the addition of nearly 600 GWp. Consequently, total installed PV capacity surpassed 2.2 TWp by the end of the year, doubling in less than three years and highlighting the technology's accelerating global uptake [1]. According to the International Renewable Energy Agency (IRENA), the total installed cost of utility-scale PV projects also declined by 11% year-on-year, from USD 777/kW in 2023 to USD 691/kW in 2024, representing an 87% reduction since 2010 [2]. Although PV

*Corresponding author – e-mail: aalabbasi@derasat.org.bh

Received 13.02.2026 | Accepted 20.05.2026 | Published 03.08.2026

are expanding globally, various implementation challenges persist, highlighting the need for context-specific deployment strategies. Land availability is a notable constraint, particularly in small countries and island states. For example, in the Canary Islands, limited land resources have prompted efforts to evaluate rooftop PV potential as an alternative to support renewable energy goals [3]. Access to finance is another major barrier, especially in economically unstable regions. In Sudan, for instance, limited affordability and the absence of de-risking mechanisms have slowed rooftop solar PV adoption, despite high solar potential [4]. Grid infrastructure can also limit integration, especially where transmission and distribution systems are weak. In Kenya, issues with grid reliability and centralised control have posed challenges for PV deployment [5].

To overcome such barriers, especially in space-constrained and islanded settings, spatial analysis and simulation tools have become essential for optimizing PV system design and viability. For instance, tools such as PVsyst, ArcGIS, and RETScreen have been employed for accurate system modeling, economic feasibility analysis, and environmental impact assessment, particularly in building-integrated PV scenarios where rooftop constraints are critical [6]. Additionally, Geographic Information Systems (GIS) combined with Multi-Criteria Decision Analysis (MCDA) methods enable optimized site selection in regions with topographical and infrastructural limitations, such as Saudi Arabia's Al-Qassim region, where 17.5% of the area was identified as highly suitable for solar PV installations [7].

It is important to highlight that the integration of spatial analysis tools with financial simulation platforms is increasingly facilitated through VPP models. VPPs aggregate distributed PV systems and utilize real-time data, forecasting algorithms, and optimization techniques to coordinate energy dispatch and participate in electricity markets. In Australia, VPP implementations that combine rooftop PV mapping, demand forecasting, and battery integration have resulted in household energy cost reductions of up to 24% and internal rates of return exceeding 11% [8]. Moreover, financial simulation approaches, such as risk-averse bidding strategies, enable PV operators to manage market uncertainty while enhancing profitability [9].

To illustrate its applicability, the framework is applied to the case of Bahrain, where solar energy is projected to reach an installed capacity of 300 MW and generate approximately 510 GWh annually by 2030, resulting in estimated cost savings of BHD 32M (USD 83M) [10]. Despite this promising outlook, solar PV currently accounts for only a marginal share of total electricity generation, with natural gas continuing to dominate the energy mix [11]. This limited uptake is primarily attributed to two challenges:

Bahrain's constrained land area (~780 km²) and the relatively low level of private sector participation in the renewable energy development, in contrast to Dubai, where strong private engagement has significantly accelerated renewable deployment [12].

Accordingly, the paper is organised as follows. Section 2 outlines the proposed methodology, including the analytical framework, modelling tools, and the data employed for the case study of Bahrain. It also details the application of the approach to assess spatial suitability. Section 3 presents the results of the geospatial and financial analyses, focusing on three deployment scenarios, 0.5MW, 1 MW, and 1.5 MW, along with their corresponding financial evaluations. Section 4 presents the effects of each pricing policy on the investor, regulator, and consumers. Section 5 acknowledges the limitations and proposing avenues for future research. Finally, Section 6 concludes the study by summarising the key findings.

2 Methodology

This study proposes a multi-stage framework for the implementation of a VPP model tailored to off-site solar PV deployment. The framework integrates spatial analysis, technical simulation, and financial evaluation to assess the feasibility of distributed PV aggregation within a VPP structure. The methodology is designed to be adaptable to countries facing land constraints and limited private sector engagement in renewable energy development.

The proposed framework consists of the following stages:

- Site Selection through Remote Sensing and GIS Analysis to identify technically viable rooftops or land parcels based on spatial and environmental suitability.
- PV System Simulation using PVsyst – to model energy yields and assess technical system performance under local climate and design parameters.
- Financial Evaluation and VPP Structuring to assess investment returns and the feasibility of integrating distributed systems into a coordinated VPP model.

To demonstrate its applicability, the framework is applied to the case of Bahrain a small island nation with limited land availability and an evolving renewable energy policy landscape. The focus of the application is an off-site solar PV system modelled for technical and financial viability within a potential VPP configuration.

2.1 Site Selection through Remote Sensing and GIS Analysis

Preliminary site identification was conducted using high-resolution satellite imagery and GIS tools. The selection process aimed to identify technically viable areas for rooftop or ground-mounted solar installations. Candidate sites were evaluated based on the following geospatial and environmental criteria found in [13], [14], and [15]:

- Solar irradiance levels (kWh/m²/day).
- Land suitability and topography (slope < 60°, non-shaded).
- Proximity to surrounding buildings the national grid infrastructure (within 700 meters of low-voltage feeders to minimize the losses).
- Ambient temperature and exclusion zones (e.g., water bodies, heritage sites, industrial hazards).

These criteria were selected particularly because they are the most frequently adopted in literature and directly affect the energy yield. This spatial screening process produced a shortlist of suitable sites distributed across various urban and semi-urban areas. The final selection, as highlighted in Figure 1, for simulation focused on the most promising location, which provided adequate surface area for a 1 MW system, favourable solar exposure, and minimal grid interconnection barriers.

Figure 1: (a) Solar image for the site location. The selected rooftops (in green) based on the geospatial and environmental criteria.

2.2 Rooftops Owners Compensation Methods

Three possible ways can be offered to convince people to use their rooftops for installing the VPP as follows:

- Percentage of the profit: they can receive a fixed percentage from the annual profit e.g. 10 to 15% according to the PV rating installed.
- Electricity at subsidized tariff: a fixed amount of kWh monthly at cheap price compared to the market price e.g. 1000 kWh monthly at 3 fils/kWh (0.79 cents/kWh). In addition, a guaranteed energy stored in the batteries in case of losing grid supply.
- Both money and electricity: determined in the negotiations with the rooftop owner.

2.3 PV System Simulation Using PVsyst

In the second phase, the technical performance of 0.5MW, 1 MW, and 1.5 MW PV systems were simulated using PVsyst 8.0.14. The simulation incorporated site-specific meteorological inputs from Photovoltaic Geographical Information System (PVGIS), along with system design specifications representative of current market standards:

The simulation produced detailed performance outputs, including:

2.3.1 Annual energy generation (MWh/year)

This indicates the approximate total amount of generated energy throughout the year. Figure 2 specifies the daily energy average for each month for 1MW scenario.

2.3.2 Performance Ratio (PR)

It is the ratio of the actual energy produced, with respect to the nominal energy production at STC [18]. Typical PR values in the last years range from 0.6-0.9 [19].

Table 1: The components specifications used in the simulation [15], [16], [17].

Component Name	Specifications and Standards
Solar Module	720W Mono-crystalline PV modules and efficiency of at least 21% with 25 years guarantee
Inverter	Efficiency of at least 95% with at least 10 years guarantee
Mounting	Fixed tilt mounting structure and optimised for local latitude
Solar Cables	Withstand current, voltage and heat limits and voltage drop percentage should not exceed 3%

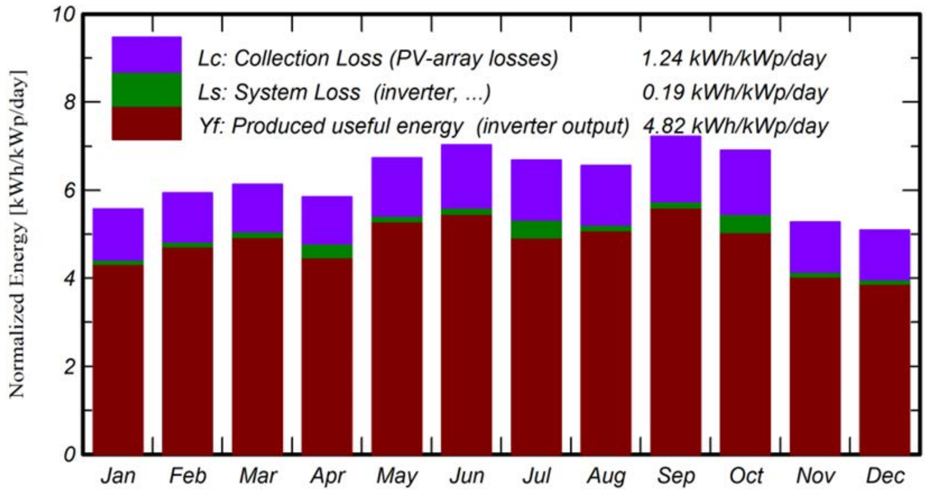


Figure 2: Daily normalized energy production average for each month from PVsyst.

$$PR = \frac{Y_f}{Y_r} \tag{1}$$

Where Y_f represents final energy yield and Y_r represents the refence energy yield of the PV plant [19].

Table 2 summarises the energy yield, performance ratio and area required by each VPP size after running the simulation.

2.3.3 System losses breakdown

It provides the energy flow at each stage from the available solar energy to the energy injected to the grid in details. This helps to find the system overall efficiency which in the case of 1MW equals to 82.8% as shown in Figure 4.

2.3.4 Shading impact analysis

PVsyst provides 3D drawing tools to insert the PV panels and their surroundings, as in Figure 5, which helps to estimate the shading factor values. It is essential to include the shading effect in the simulation to get more realistic and accurate results.

These results served as the technical baseline for assessing the viability of the system as part of a larger VPP structure. The energy profile was later used to evaluate potential contributions to aggregate dispatch, financial performance under different tariff conditions, and

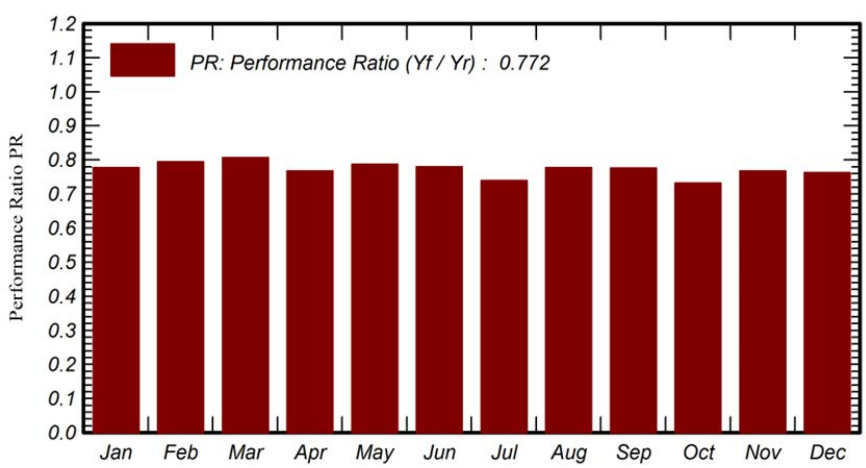


Figure 3: Performance ratio of each month.

Table 2: Summary of the main results for the three scenarios.

Power Capacity (MW)	Energy Injected in the First Year (MWh)	Performance Ratio (%)	Area Covered (m^2)
0.5	1,049.5	77.95	2,586
1.0	2,052.7	77.18	5,109
1.5	3,093.2	76.58	7,759

integration challenges within Bahrain's existing energy infrastructure.

3 VPP Structuring and Investor Engagement Options

The third stage of the framework focuses on structuring a VPP model that not only aggregates distributed solar PV systems but also creates attractive conditions for investor participation. The proposed VPP functions as a digital aggregator that coordinates the performance, dispatch, and market interaction of geographically dispersed solar systems. To align with Bahrain's existing policies and regulatory environment, particularly the national net metering and PPA schemes, VPPA is proposed as a possible alternative among many other pricing options. Without a market infrastructure there cannot be any existence of a virtual power plant which is definitely not the case with a microgrid (MG) [20].

3.1 Net Metering-Linked VPP Model

This structure leverages Bahrain's current net metering policy, which allows eligible customers to offset their electricity bills by exporting excess solar energy to the grid as shown in Figure 7. The investor rent the PV setup to the consumers on a fixed monthly or annually-basis fee from the consumers. The VPP aggregates multiple participants (residential, commercial, or institutional) under a unified management system, optimising generation and consumption across sites. For investors, this model offers a relatively low-risk entry point by relying on existing billing mechanisms and guaranteed grid access. In addition, the initial investment required for this mechanism is relatively low because storage systems are not essential. Figures 8 and 9 show the estimated capital cost and the levelized cost of energy (LCOE) for different VPP sizes considering the economy of scale effect [21] as in equation 2. The reference values are considered based on a 500kW solar power system at King Faisal University, Alahsa, Saudi Arabia [22].

$$C_2 = C_1 \left(\frac{S_2}{S_1} \right)^{Sf} \quad (2)$$

where C_2 is the estimated desired plant cost, C_1 is the reference plant cost, S_2 is the desired plant size, and S_1 is the reference plant size, Sf is the scaling factor.

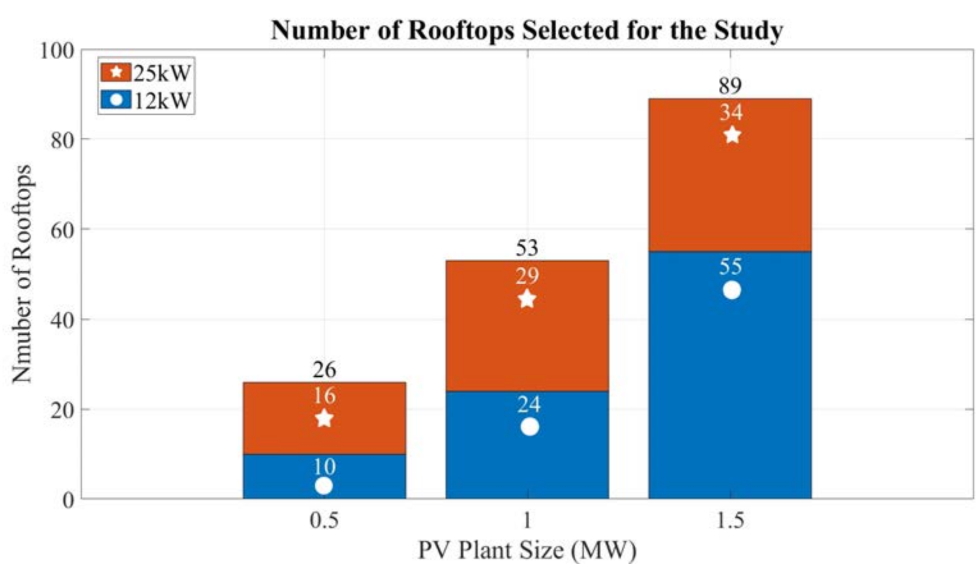


Figure 4: Number of rooftops selected for each VPP size.

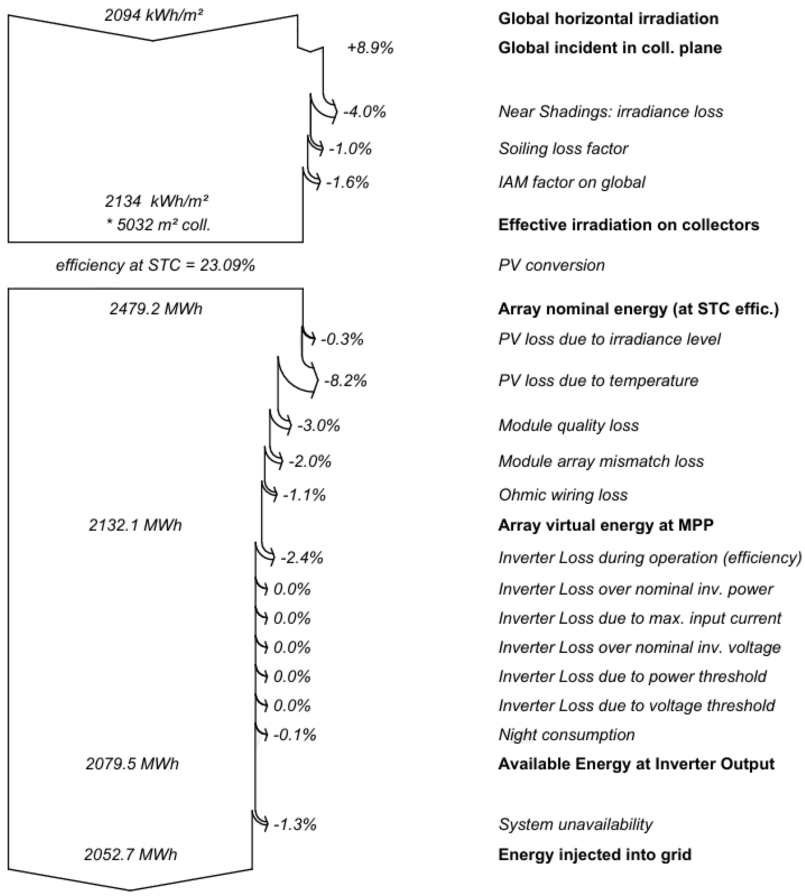


Figure 5: Energy loss diagram of the PV system.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (3)$$

Where I_t is the initial cost, M_t is the operation and maintenance cost, F_t is the fuel cost, which is zero for PV energy, E_t is the energy generated at period t, and r is the discount rate [23].

However, using net metering to support Virtual Power Plants (VPPs) faces two main challenges that could slow its growth and limit its potential. The first is practical: the system depends on a direct connection to the grid for customers to receive bill credits, which reduces flexibility and makes it harder to scale. The second, and more significant for Bahrain, is economic. Because electricity tariffs for citizens are heavily subsidized starting as low as 3/9/16 fils/kWh equivalent to 0.79/2.4/4.2 cents/kWh [24] the financial incentive to export surplus power through net metering becomes very weak with the higher rent fee. This creates a clear disincentive for household participation between citizens and residents.

3.2 Power Purchase Agreement (PPA)

One of the methods to overcome the economic potential of a VPP under a net metering framework is to formally recognize it as a power generation entity. This would enable the VPP investor to sign a PPA with the grid regulator at a fixed tariff, operating within Bahrain's single-buyer model much like the Independent Power Producers (IPPs) already active in the country. While this approach offers revenue certainty and a degree of investment security, it may not necessarily optimize profitability. Given the relatively low LCOE for solar PV, and the fact that the regulator remains the sole buyer, the potential for value maximization could be constrained. The VPP can be easily scheduled with the rest power plants to ensure proper coordination with the

Figure 6: Shading effect on some of the selected rooftops in PVsyst.

Automatic Generation Controller (AGC). Figure 10 illustrates the PPA structure.

3.2 Virtual Power Purchase Agreement (VPPA)

This option proposes introducing time-differentiated electricity pricing within the VPP framework based on the supply and demand in the electricity market as demonstrated in Figures 11 and 12.

The VPP operator injects power in the grid and receives credits that can be exchanged with money from the consumers as shown in Figure 13. Therefore, it is necessary to have a platform that allow the VPP investor

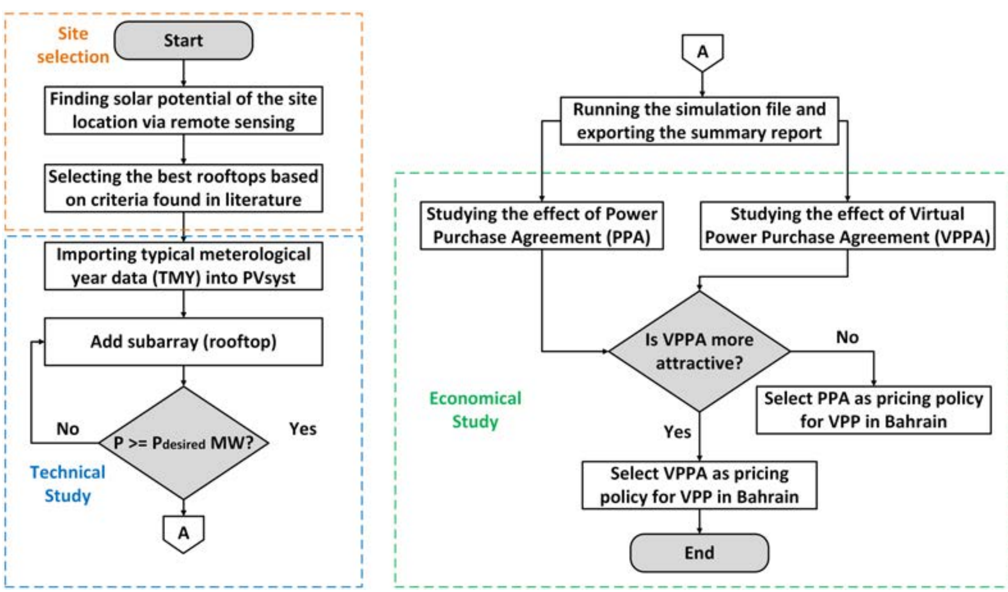


Figure 7: Research procedure flowchart.

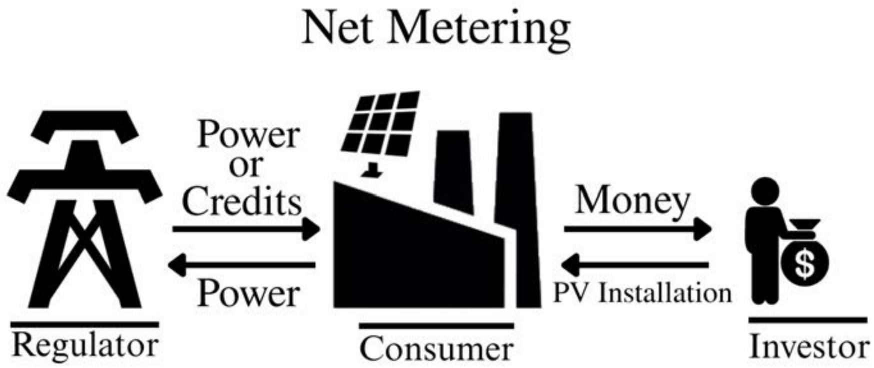


Figure 8: Net metering policy structure.

to make different types of deals with any customer from everywhere across the country without the need for physical connection between the VPP and the consumer. This will increase the potential market size and the probability to have better deals and consequently maximizing the profit from the VPP.

In addition, the consumers can pay less for their electricity bill through buying the credits available on the platform which makes it attractive for them to participate in the renewable energy transition.

4 Results & Discussion

In this section, a comparison between the three pricing options is presented to determine the better option that aligns with Bahrain context. Other options such as fixed VPPA and private wire agreement are excluded. Because the first one is almost the same as PPA, and the second one requires a written license issued by the Minister of Water and Electricity under the conditions issued by the Council of Ministers decision as stated in [28]. There are

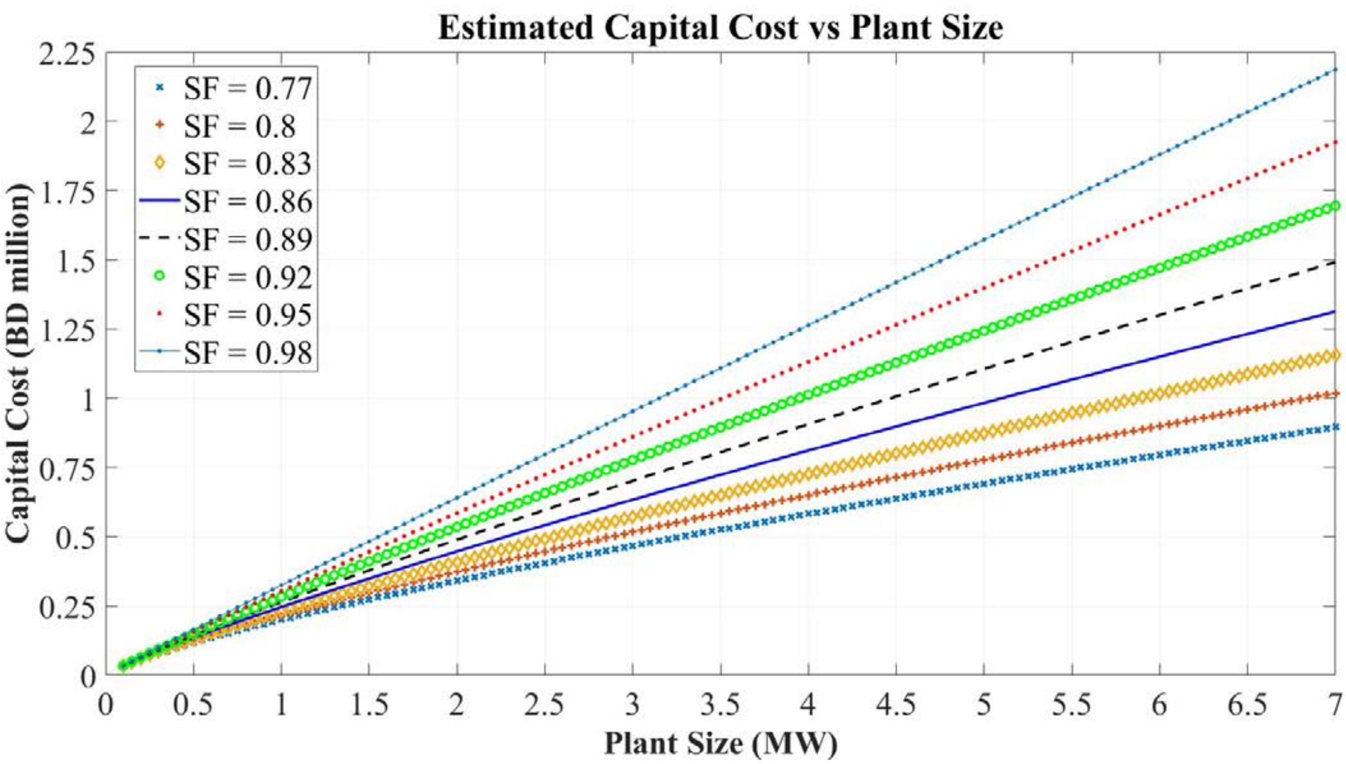


Figure 9: The estimated capital cost for different PV plant sizes based on economies of scale scaling factors.

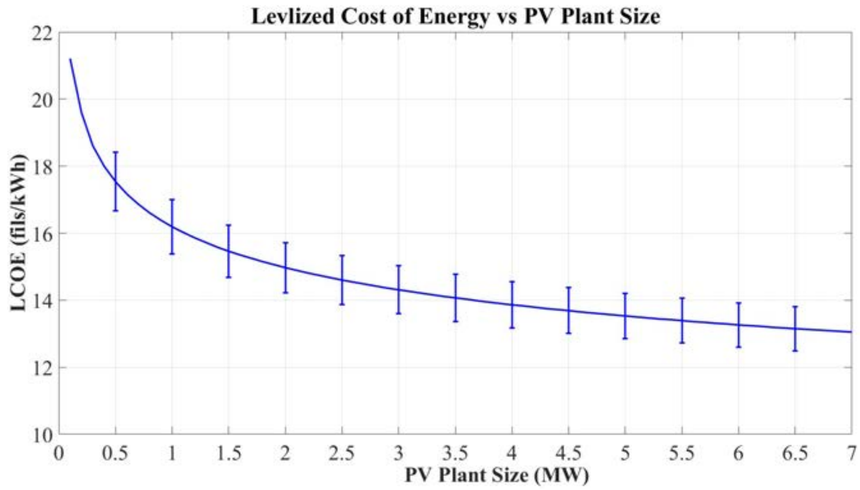


Figure 10: The estimated LCOE for different PV plant sizes with 5% error.

many stakeholders in the electricity market, but the key players that will be considered in this study are the regulator, investors, and consumers because they have direct relationships with each other. The assumptions made for the economic study are listed in Table 3.

4.1 Investor Point of View

Private sector investments can play a vital role in accomplishing net zero emissions in Bahrain by 2060. In net metering the investor receives a fixed lease from the consumers, and the regulator offset their bills accordingly. In PPA the investor receives money from the regulator at a fixed price. While in VPPA the investor exchanges the credits received for each kWh injected in the grid with money from the trading with the consumers virtually. The VPPA has the largest market size and thus can be more profitable for the investor. One of the metrics used for assessing the three pricing mechanisms in this study is the Net Present Value (NPV) as in Equation 4 [28]. By comparing the results shown in Figure 14, most of the cases have positive NPV which makes them economically viable in general. Net metering has the highest NPV because it requires less initial cost than the two other options e.g. BHD 370k (approximately USD 980k) for 1.5MW at 25.6 fils/kWh (6.8 cents/kWh). While VPPA is usually more profitable than PPA in which during low average demand for 1.5MW (the red line in Figure 14c - BHD 141k or USD 373.5k) the NPV is almost the same as the maximum that PPA can reach. However, due to the dynamic prices it can optimize the revenue to reach at least 40% more than PPA (upper blue line- BHD 198k or USD 524.5k) and

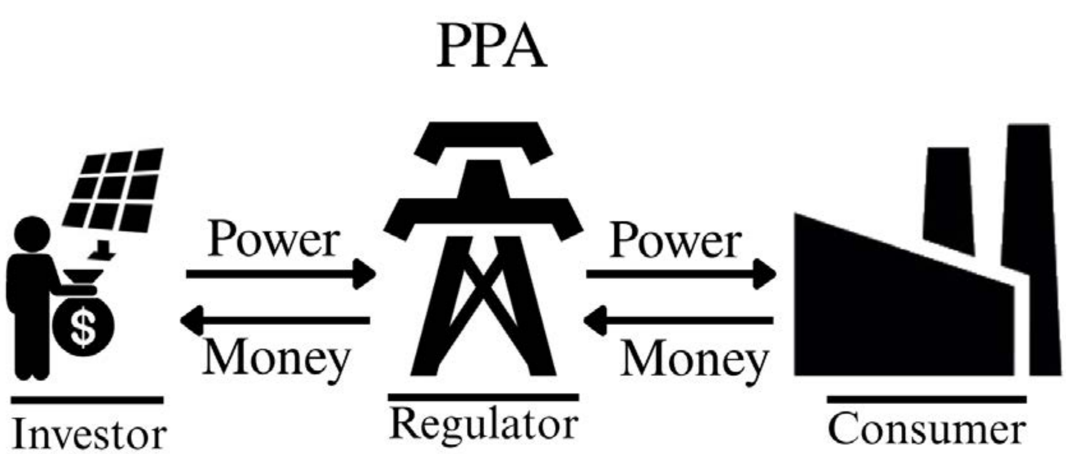


Figure 11: PPA policy structure.

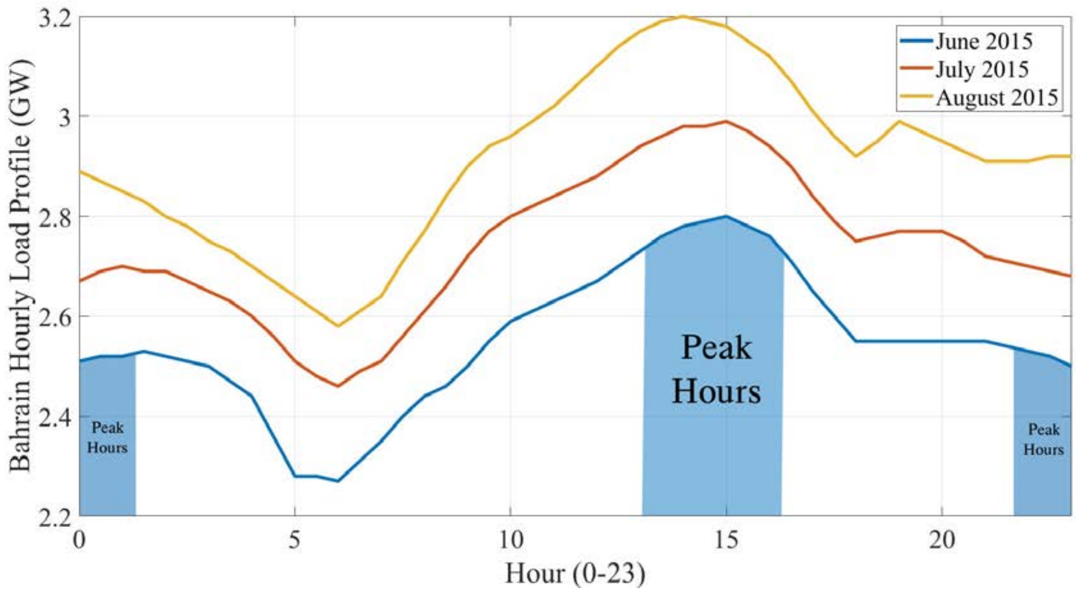


Figure 12: Peak hours in Bahrain. Based on data from [25].

about 70% more in the ideal case (upper black line - BHD 242k equivalent to USD 641.1k).

$$NPV = \sum_{n=0}^{N} \frac{CF_n}{(1+i)^n} \quad (4)$$

Where CF_n is the net cashflow at year n, i is the discount rate, n is the time period, and N is the total number of time periods.

Another economic metric is Discounted Payback Period (DPBP) as in equation 5 [29] to find the year when the expenses and revenue are expected to breakeven.

$$\text{DPBP} = y + \frac{|n|}{p} \quad (5)$$

Where n is the period preceding the period in which the cumulative cash flow turns positive, |n| is the absolute value of the cumulative discounted cash flow in period y, p is the discounted value of the cashflow of the period in which the cashflow turns positive.

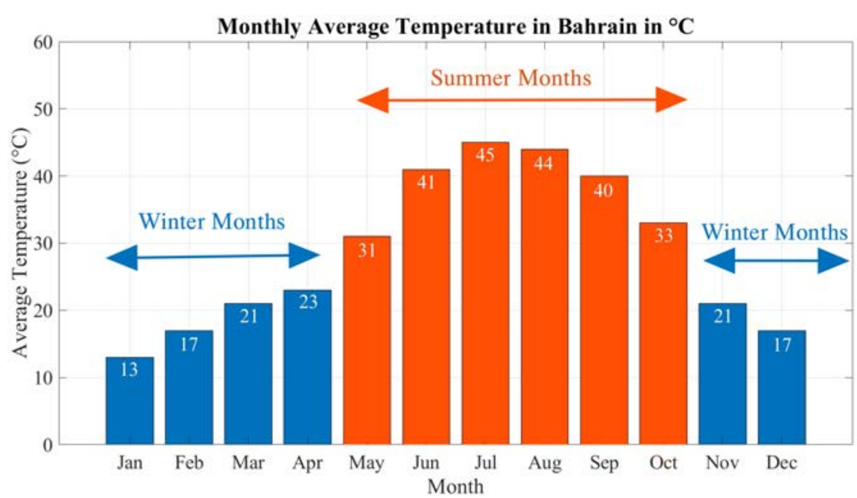


Figure 13: Summer and winter months in Bahrain. Based on data from [26].

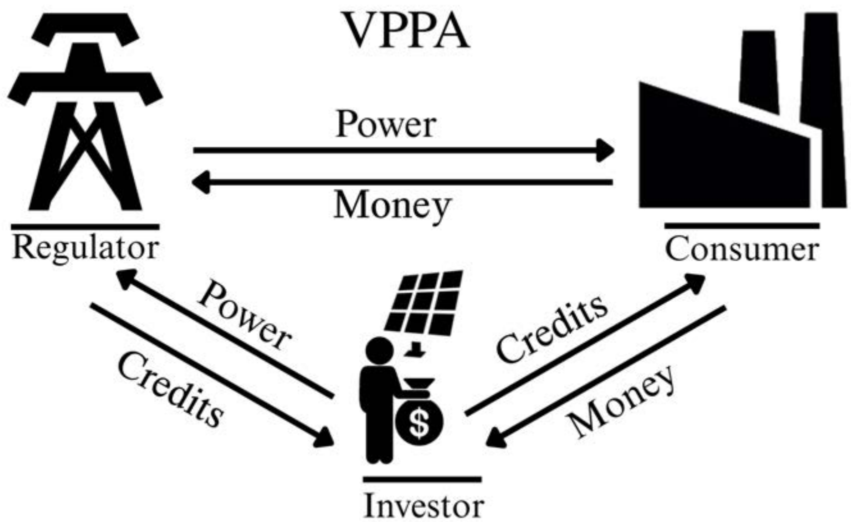


Figure 14: VPPA policy structure.

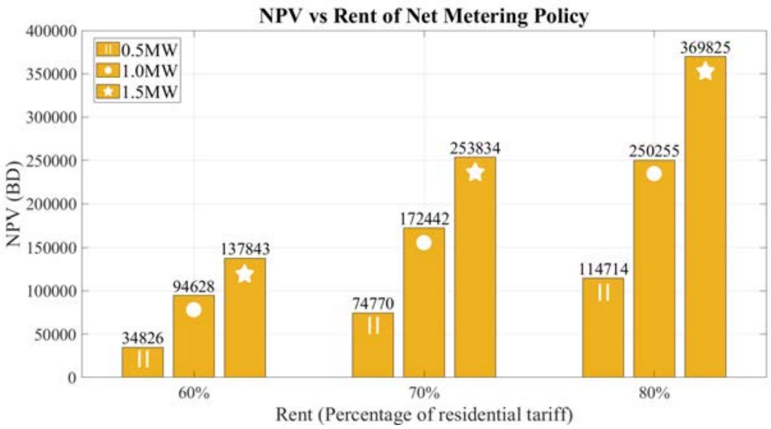
The estimated DPBP are recorded in Table 4. The payback periods between all the pricing structures are relatively close to each other which means all of them are economically viable. Net metering lease has the biggest margin difference (3 to 4 years) between the lowest and highest price might be set by the investor. Although VPPA has higher initial cost than net metering due to the need for batteries, both almost breakeven at the same period as the plant size increases. This emphasizes that VPPA can be applied as the investor will benefit from the larger market size and dynamic prices based on supply and demand.

4.2 Regulator Point of View

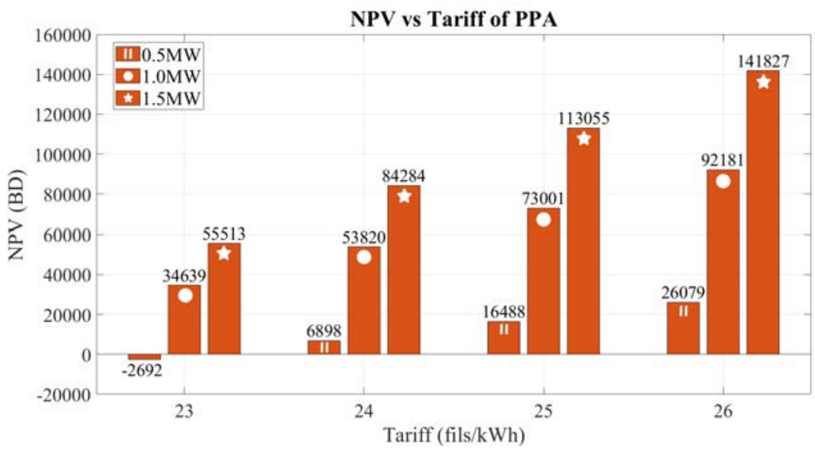
The power supplying cost will be less on the regulator because the VPP is much closer to the load centre than conventional power plants, which means less infrastructure is required in the transmission and distribution phases. Because the power generated by the VPP is directly injected into the grid with PPA and VPPA, the grid regulator can schedule and dispatch the VPP to optimize the grid operational cost according to the demand using different strategies such as day-ahead scheduling (DAS), and hour-ahead scheduling as studied in [31] This will limit CO_2 emissions level from the energy sector which can be found using equation 5. In the VPPA structure, the regulator acts as the broker between the VPP owner and the consumer via a trading platform. It can get a percentage of each electricity credits transaction operation to cover its transmission and distribution cost (7 fils/kWh or 1.9 cents/kWh) [27], or to make profit from this service. Unlike the net

Table 3: Economic analysis assumptions.

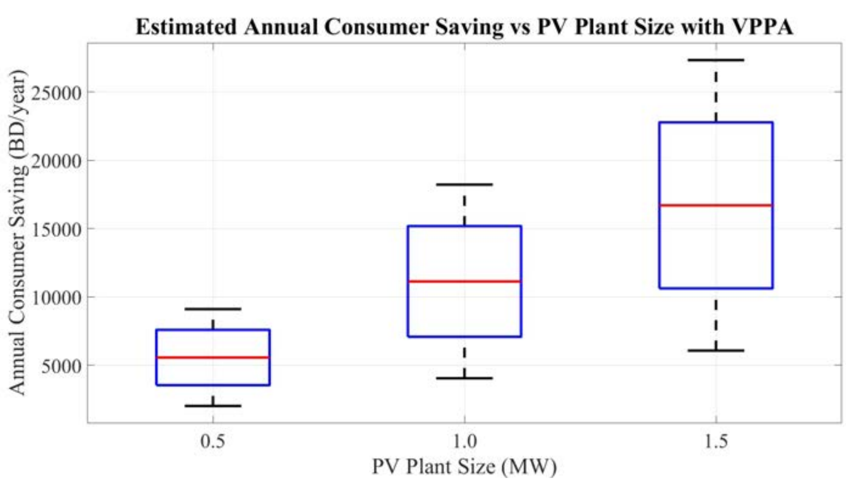
Item	Assumption
Solar Modules	25 years lifespan with 0.5% annual degradation factor.
Inverter	Replaced after 13 years.
Batteries	Replaced after 13 years and form roughly 60% of the VPP size for output stabilization. Only required in case of PPA and VPPA because all the power is directly injected into the grid not only the surplus in case of net metering.
Operation and Maintenance Cost (OPEX)	1% of the capital cost (CAPEX) and increase by 2% annually. The rooftop owners get 15% of annual profit in case of PPA and VPPA.
Discount Rate	7% (End of Period).
Inflation Rate	2% annually.
Electricity Distribution Cost	In VPPA scenario, both the VPP owner and the consumer should pay the distribution cost of 3.7 fils/kWh (0.98 cents/kWh) [27] equally to ensure that the grid regulator will be able to cover its operating costs.



(a)

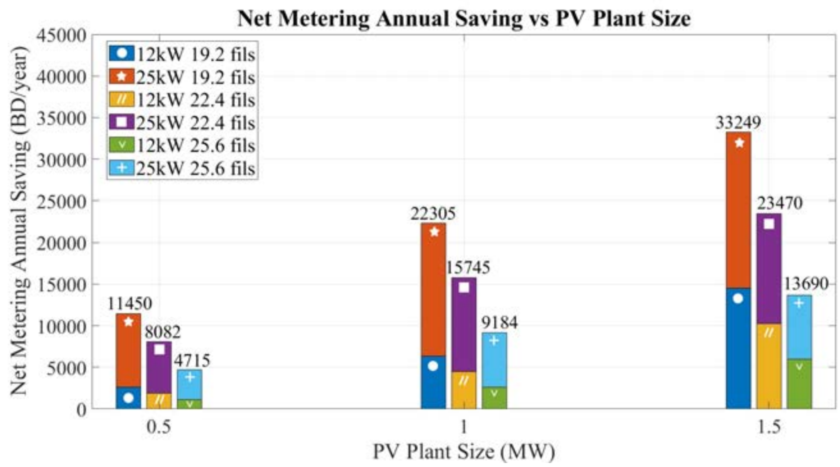


(b)

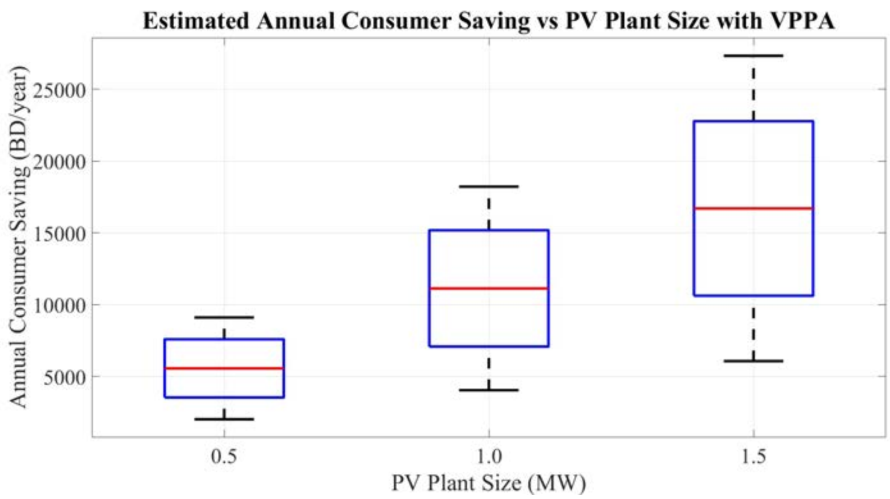


(c)

Figure 15: The estimated NPV in BHD for different pricing structures for different plant sizes. a) Net metering rent depends on the percentage of domestic tariff and the expected average energy yield of the PV system over 25 years (60% = 19.2 fils/kWh or 5.1 cents/kWh, 70% = 22.4 fils/kWh or 5.9 cents/kWh, 80% = 25.6 fils/kWh or 6.8 cents/kWh). b) PPA tariff depends on the LCOE of the Solar PV and Request for Proposal (RFP) process. c) VPPA has a dynamic tariff that varies from 23 to 30 fils/kWh (6.1 to 7.9 cents/kWh) based on the supply and demand of electricity credits in the market.



(a)



(b)

Figure 16: The estimated annual electricity bill savings in BHD/year. a) Total annual consumers saving with net metering considering the lease and the bill offset. b) The estimated annual saving from buying all the plant credits.

metering, which is more difficult to dispatch because the power injected depends on the surplus power of the consumers which is variable and unpredictable.

$$CO2_{mitigated} = E_{PV} \times (GCI - PV_{Emissions}) \qquad (6)$$

Where E_{PV} is PV plant energy yield in MWh, GCI is the Grid Carbon Intensity in $kgCO_2/MWh$ (489 $kgCO_2/MWh$ in Bahrain) [31], $PV_{Emissions}$ is the solar lifecycle emissions (41 $kgCO_2/MWh$) [32].

4.3 Consumers Point of View

Consumers concern about the tariff system that would be adopted with the rapid growth of distributed energy resources (DERs). Net metering can help the limited consumers save money due to the need for physical

Table 4: The estimated discounted payback period in years for different pricing mechanisms.

VPP Size (MW)	Net Metering (years)	PPA (years)	VPPA (years)
0.5	11.7-7.9	11.3-10.6	10.9-8.7
1.0	10.6-7.2	11.0-9.1	10.0-7.8
1.5	9.9-6.8	10.1-8.4	9.1-7.2

Table 5: Estimated annual CO_2 emissions saving for different plant sizes.

VPP Size (MW)	CO_2 Mitigated (tons CO_2/year)
0.5	426.135
1.0	852.27
1.5	1278.41

connection so only the rooftops owners will benefit from this structure. PPA has no influence on the tariff as it is an agreement between the investor and the regulator. On the other hand, VPPA can contribute to reducing the tariff for all consumers regardless of DER installation. Figure 15 presents the approximate saving that a consumer can make from the different pricing mechanisms. Both options seem to have similar saving amount when comparing between Figures 15a and 15c assuming that the net metering lease price is determined at 22.4 fils/kWh (5.9 cents/kWh) times the expected energy yield which is an average price for the investor. However, the net metering numbers are based on aggregated saving from all the consumers, and the individual saving can be found from the total saving and the number of PV systems installed with their ratings in Figures 15a and 15b respectively.

In contrast, the VPPA saving can be made by one consumer alone through buying all the plant credits or portion of it at the time with low demand. By comparing the individual saving for 1.5MW PV plant at all the net metering leases, each consumer (12kW/25kW) will save roughly 264/550, 187/389, and 109/227 BHD/year equivalent to 700/1457, 495/1030, and 289/601 USD/year respectively. While a single consumer can save from VPPA starting from BHD 10.6k (approximately USD 28k) up to BHD 22.8k (USD 60.4k) for 1.5MW PV plant which is a significant saving. This feature can make the consumers try their best to get as much credits as they can at competitive prices which will make the market active.

5 Future Work

Further work can be done to investigate the impact of a virtual market platform with the capability of allowing peer-to-peer (P2P) trading, how to maximize the profit through intelligent control. This work assumes that all the PV systems installed are new but for the people who would like to join a VPP with their own assets for the case

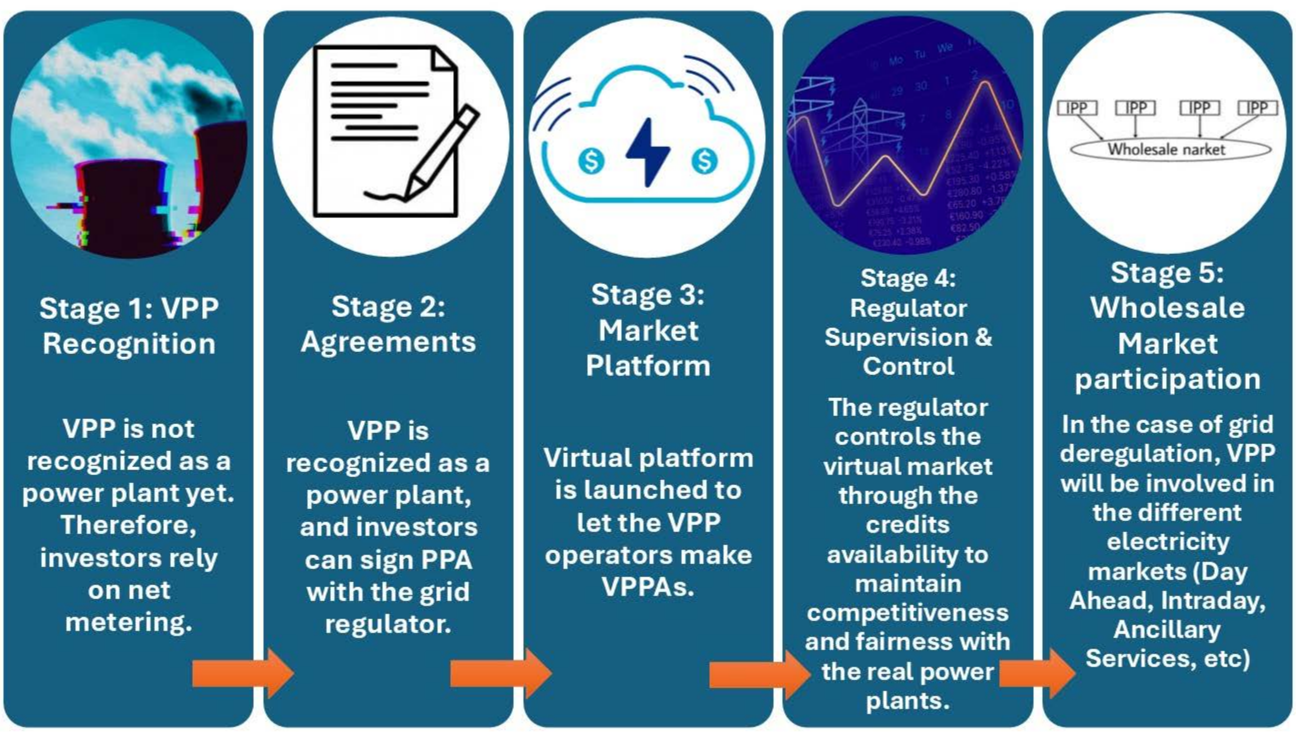


Figure 17: The proposed stages to establish VPPs in Bahrain.

of Bahrain need further work. Moreover, the effect of grid deregulation on the electricity market in Bahrain, and the legal measures required to establish VPP on rooftops. As shown in Figure 16, the first two stages are investigated in this research, and the rest are left for the future.

6 Conclusion

In conclusion, this paper proposes a multi-stage framework for proposing a VPP model for off-site solar deployment in Bahrain with three different sizes 0.5MW, 1MW, and 1.5MW. The framework begins with technical study to determine the best rooftops for PV installations based on selection criteria and the approximate annual energy yield through PVsyst software simulation: 1,049.5MWh, 2,052.7MWh, and 3,093.2MWh respectively. Then an economic study should be conducted to assess the feasibility of VPP implementation based on three economic metrics: NPV, DPBP, and percentage of savings taking into consideration discount rate of 7% economy of scale, and inflation rate of 2%. Three points of view should be considered in the economic assessment: investor, regulator, and consumers. Since renewable energy integration requires big investments which is not always affordable by one side. Therefore, external investors play vital role in the growth of renewable energy integration. However, setting a proper policy to attract external investments is a crucial aspect and this paper studied the adoption of net metering, PPA, and VPPA pricing mechanisms. The best mechanism is the one can make all sides win because they directly affect the energy market. Net metering has the highest NPV from BHD 35k to 370k (USD 92.7k to 980.2k) and shortest DPBP between 11.7-6.8 years due to less initial and operation and maintenance costs.

However, the need for physical connection in which the rooftops owners are the only consumers, and the subsidized electricity tariff for Bahraini residential accounts will not encourage citizens to allow the investor to use their rooftops to participate within the VPP through net metering. PPA offers a low-risk solution for the subsidized electricity tariff in which the rooftops owners (the VPP participants) will get either money, electricity, or both. But the PPA price most probably will not reflect the maximum economic potential of the VPP from BHD -2.7k to 142k (USD -7.15k to 376.2k) due to low LCOE of PV energy and the single-buyer model electricity market in Bahrain. In addition, the consumers will still pay the same electricity tariff as PPA is only between the VPP investor and the grid regulator. While VPPA is an alternative that benefits all the sides. The investor will receive less profit than net metering but at least 40% more than PPA and without connection and subsidized tariff issues. The regulator will be responsible on supervising the virtual market and will receive a percentage from each transaction operation to cover the operational cost of the grid. The consumers can benefit from the electricity credits to make significant bill saving from BHD 3.5k to 23k (USD 9.27k to 60.93k) comparing with the net metering from BHD 109 to 550 (USD 288.41 to 1455.3) per individual especially for the big commercial and industrial loads regardless of their location. The VPP participants will be compensated for using their rooftops and as the installed PV system size increases, the more profitable it will be and thus the share of the profit will increase. Overall, net metering is the best option for investors, despite it has some limitations that might prevent it from expand easily. PPA is the best option from the regulator point of view since it can dispatch the VPP and has relatively larger profit margin in case of any sudden changes in the energy market prices globally. But the consumers will still pay their bills at the same tariff rate, and it has the least profit along 25 years for investors. VPPA is a compromise for all the sides as it offers acceptable profitability for the investor, control and supervision for the regulator, and significant annual saving for the consumers. Finally, implementing VPP is feasible in Bahrain and that can help in overcoming the limited land availability problem and contribute to achieving net zero emissions vision by 2060.

Acknowledgements

Sincere thanks to all those who contributed to this research. Especially the Electrical and Electronics Engineering Department at the University of Bahrain and Eng. Ebrahim Al-Burshaid for providing the solar images, data, and 3D shapes of the site buildings.

References

[1] Jäger-Waldau A, Snapshot of photovoltaics, March 2025, EPJ Photovoltaics 16 (2025) p22. https://doi.org/10.1051/epjpv/2025012

[2] International Renewable Energy Agency, Renewable power generation costs in 2024. Abu Dhabi: IRENA; 2024. https://www.irena.org/media/Files/IRENA/Agency/Publication/2025/Jul/IRENA_TEC_RPGC_in_2024_2025.pdf

[3] Schallenberg-Rodríguez A, Photovoltaic techno-economical potential on roofs in the Canary Islands, Renewable and Sustainable Energy Reviews 18 (2014) p 75-86. http://dx.doi.org/10.13044/j.sdewes.2014.02.0007

[4] Ahmed TZ, Mohamed A, Ahmed ME, Abdalgader AOE, Hassan-Sayed MG, Investigating energy policies to boost grid-connected rooftop solar PV in Sudan, Clean Energy 7 (5) (2023) p 994-1005. https://doi.org/10.1093/ce/zkad044

[5] Millan L, Atela J, The untapped potential of solar energy in Kenya: Factors limiting the integration of solar PV into the electricity grid. (2017). https://acts-net.org/wp-content/uploads/Working-Paper-0052017.pdf

[6] Asif M, Hassanain MA, Nahiduzzaman KM, Sawalha H, Techno-economic assessment of application of solar PV in building sector: A case study from Saudi Arabia, Smart and Sustainable Built Environment 8 (1) (2019) p34-52. https://doi.org/10.1108/SASBE-06-2018-0032

[7] Alhammad A, Sun Q, Tao Y, Optimal solar plant site identification using GIS and remote sensing: Framework and case study, Energies 15 (1) (2022) p 312. https://doi.org/10.3390/en15010312

[8] Behi B, Baniasadi A, Arefi A, Gorjy A, Jennings P, Pivrikas A, Cost–benefit analysis of a virtual power plant including solar PV, flow battery, heat pump, and demand management: A Western Australian case study, Energies 13 (10) (2020) p 2614. https://doi.org/10.3390/en13102614

[9] Xiao D, Qiao W, Qu L, Risk-averse Offer Strategy of a Photovoltaic Solar Power Plant with Virtual Bidding in Electricity Markets. In: 2019 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT). IEEE; 2019. p. 1-5. https://doi.org/10.1109/ISGT.2019.8791618

[10] Alnaser NW, Alnaser W, Al-Kaabi E, Evaluating solar and wind electricity production in the Kingdom of Bahrain to combat climate change, Frontiers in Built Environment 9 (2023). https://doi.org/10.3389/fbuil.2023.1210324

[11] International Renewable Energy Agency, Renewable Energy Markets: GCC 2023. Abu Dhabi: IRENA; 2023. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Dec/IRENA_Rnewable_energy_markets_GCC_2023.pdf

[12] Al-Sarihi A, Mansouri N, Renewable energy development in the Gulf Cooperation Council countries: Status, barriers, and policy options, Energies 15 (5) (2022) p 1923. https://doi.org/10.3390/en15051923

[13] Alhmoud L, Shloul M, Impact of wheeling photovoltaic system on distribution low voltage feeder, Results in Engineering 19 (2023) p 101378. https://doi.org/10.1016/j.rineng.2023.101378

[14] Urs RR, Ali Z, Marzband M, Saleem K, Mohammadi-Ivatloo B, Anvari-Moghaddam A, A technical assessment on photovoltaic power generation under varying weather profile – Northumbria university pilot. In: 2020 IEEE 29th International Symposium on Industrial Electronics (ISIE). IEEE; 2020. p. 811-815. https://doi.org/10.1109/ISIE45063.2020.9152460

[15] Electricity & Water Authority, Technical Expert to develop grid connection guidelines and standards for the Kingdom of Bahrain: Solar PV Connection Guidelines for Customers and Installers. Kingdom of Bahrain: Electricity & Water Authority. https://legacy.ewa.bh/en/Media/Documents/Solar%20PV%20Connection%20Guidelines%20for%20Customers%20and%20Installers%20.pdf

[16] Connect to long-term success with the right DC cables for PV plants. PV Tech; 2023. https://www.pv-tech.org/industry-updates/connect-to-long-term-success-with-the-right-dc-cables-for-pv-plants/.

[17] Pennsylvania State University College of Earth and Mineral Sciences, Voltage drop in solar systems. Pennsylvania State University; 2024. https://courses.ems.psu.edu/ae868/node/967.

[18] *Performance Ratio (PR) – PVsyst documentation*, PVsyst, 2023. https://www.pvsyst.com/help/project-design/results/normalised-performance-index.html

[19] Khalid AM, Mitra I, Warmuth W, Schacht V, Performance ratio – Crucial parameter for grid connected PV plants, Renewable and Sustainable Energy Reviews 65 (2016) p 1139-1158. https://doi.org/10.1016/j.rser.2016.07.066

[20] A. K. Pandey, V. Kumar Jadoun and J. N. S., "Virtual Power Plants: A New Era of Energy Management in Modern Power Systems," 2021 8th International Conference on Signal Processing and Integrated Networks (SPIN), Noida, India, 2021, pp. 538-543, doi: 10.1109/SPIN52536.2021.9566063.

[21] National Renewable Energy Laboratory, Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts. Golden: NREL. https://docs.nrel.gov/docs/fy04osti/34440.pdf

[22] S. A.-M. Ahmed, "GREEN CAMPUS INITIATIVE: DESIGN AND DEPLOYMENT OF A 500 KW ROOFTOP SOLAR POWER SYSTEM AT KING FAISAL UNIVERSITY", Research Journal of Engineering and Allied Sciences, vol. 13, no. 3, pp. 1–9, Sep. 2025.

[23] Hassan M, Yazawa N, Cong R, Scenario-Based Framework for National Energy Storage Integration in Decarbonization Pathways, International Journal of Sustainable Energy Planning and Management 47 (2025) p 7-20. https://doi.org/10.54337/ijsepm.10125

[24] Electricity & Water Authority, Tariffs. (2026). https://www.ewa.bh/en/tariff

[25] Bayram IS, Smart grids and load profiles in the GCC region, EAI Endorsed Transactions on Smart Cities 1 (3) (2017) p 153476. https://doi.org/10.4108/eai.19-12-2017.153476

[26] El-Houari H, Allouhi A, Rehman S, Buker M, Kousksou T, Jamil A, El Amrani B, Design, simulation, and economic optimization of an off-grid photovoltaic system for rural electrification, Energies 12 (24) (2019) p 4735. https://doi.org/10.3390/en12244735

[27] Sustainable Energy Unit, The Kingdom of Bahrain National Renewable Energy Action Plan (NREAP). Manama: Kingdom of Bahrain; 2017. https://www.undp.org/sites/g/files/zskgke326/files/2022-09/seu_nreap_report_2017.pdf

[28] DLA Piper, Corporate Power Purchase Agreements: Bahrain. DLA Piper Intelligence Guide; 2020. https://rise.esmap.org/sites/default/files/library/bahrain/Renewable%20Energy/Bahrain_Bahrain%20Corporate%20Power%20Purchase%20Agreements_2021.pdf

[29] Khan, M.Y. (1999). Theory & Problems in Financial Management. Boston: McGraw Hill Higher Education.

[30] Project-Management.info, Discounted Payback Period: Definition, Formula, Example & Calculator. (2020). https://project-management.info/discounted-payback-period-dpp/

[31] Pandey, A. K., Jadoun, V. K., Sabhahit, J. N., & Sharma, S. (2025). Interconnected Operation and Economic Feasibility-Based Sustainable Planning of Virtual Power Plant in Multi-Area Context. Smart Cities, 8(1), 37. https://doi.org/10.3390/smartcities8010037

[32] Electricity Maps, Electricity Maps Portal. https://app.electricitymaps.com/map/zone/BH/5y/yearly

[33] Solartech Online, How Much CO2 Does Solar Energy Save? Complete 2025 Guide. (2025). https://solartechonline.com/blog/how-much-co2-does-solar-energy-save/