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ABSTRACT

Natural gas will remain among the leading sources of energy, at least for the next few decades. Further, it is necessary to make natural gas processing operation a cost-competitive, clean, and efficient energy source, and less dependent on the grid. A comparative investigation based on two case studies is presented in this paper for a natural gas processing plant; an integration of Photovoltaic panels with Battery Energy Storage System (PV-BESS) and an integration of Photovoltaic panels with Solid Oxide Fuel cell (PV−SOFC) technologies. The aim is to be more independent from the grid for efficient operations and to reduce the emissions by introducing renewable energy in gas processing operation plant.

A techno-economic analysis is performed for both cases considering a PV capacity of 33.5 MW. The outcome of this study indicates that for 25 years of operation, the Levelized cost of electricity (LCOE) for PV-BESS is found to be 0.16 US$/kWh, and for PV-SOFC is 0.11 US$/kWh, which makes the PV-SOFC option more economical and feasible than PV-BESS. Besides, in the projected scenario where investment cost is expected to reduce, PV-SOFC's IRR is 3% and has a positive NPV of 5 Million USD$ for an internal rate of 4%. Furthermore, the LCOE for PV-SOFC in this scenario is around 0.04 USD$ per kWh, which is still less than the LCOE of PV-BESS and less than the tariff set by the Qatari electric authority for bulk industries.

1. Introduction

The world's energy has been in a transitionary evolution phase from an economy heavily depending on fossil fuels to an economy based on sustainable resources. Furthermore, clean energy has been in a quest to slow down or even stop the grand challenge of climate change and global warming.

There has been a focus on immediate, feasible, and transitionary of cleaner energy resources like natural gas, to be converted into numerous useful products efficiently to achieve long-term sustainable development goals with a clean energy system. Fossil fuels seem to be eventually depleted and come to an end, and renewable energy will become the basis for future energy [1]. The penetration of clean and renewable energy sources globally is in the range of 10%, and it is increasing [2–4]. Though, there will be a transition period from fossil fuels to clean sources. Natural gas seems to be a vital supplement to renewable energy during this transition period [5]. It can reduce emissions and increase efficiency. Additionally, the development of natural gas technologies should emphasize the conversion toward a hydrogen economy for longer-term positive impacts on the energy balance, emission reductions, and efficiency [5].

Energy generation plants today have been upsetting the environment and raise questions due to global warming. Researchers and technicians have been working to remove or at least minimize energy generation plants' effects on the environment. Song [6] emphasizes an essential fact about reducing the emission, identifying that all efforts in decreasing the emissions are based on post combustion cleaning to encounter environmental regulations in many countries. This is the case with many power and chemical plants, which are based on fossil fuels. Song suggests that efforts should be toward minimizing, removing, or stopping greenhouse gas formation at the source itself [6].

A typical gas plant, with a production of 51,000 tons of natural gas (2 BSCFD), will require 65 MW of power daily at the peak season. The Steam Turbine Generators (STG) in the gas plant generates 56 MW at high load. The shortage between the required

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demand of power and internally generated power is 9 MW, imported from the grid mainly during the summer.

The import of the 9 MW of electricity from the grid adds expense to overall operation cost and contributes to the expansion of the overall national emitted GHGs. It seems that renewable energy can be one of these effective options, especially the solar panel photovoltaic systems in locations with abundant sunlight throughout the year, mainly looking for a more practical opportunity to reduce emissions. Nevertheless, such a solution will not be enough for a gas processing plant to eliminate the requirement for importing the power from the grid. The PV system will provide power only during the day time when there is sunlight. On the other hand, the plant still will import the required electricity during the night without backup power and even during the day time on cloudy days due to its varied output. This intermittent and uncertain nature prevents broader penetration of solar and other renewables into the overall energy balance globally in addition to initial investment costs.

Solar PV requires to be backed up by another provider of energy to ensure power availability 24 h and 365 days of operations. There are two outstanding options available as a backup, battery storage and fuel cells. This study focuses on newer and cleaner technology of SOFCs (working on natural gas) as an alternative to batteries. Fuel cells have many advantages over many of the current ongoing technology on generating power; they emit fewer greenhouse gases than traditional power production and have almost no noise pollution [7]. Besides, they are used in many cases, especially with renewable energy, to suppress PV output power [8]. Eventually, SOFC is an innovative technology where its combination with traditional electrical power systems can be the future resolution in providing a high-efficiency power with low environmental impacts [9]. SOFC can increase productivity in the oil and gas energy field. It can be an excellent choice to substitute and replace battery storage in a PV system to allow for continuous generation of power. Its availability and consistency are higher than the battery storage system since SOFC can work independently from the PV during cloudy days. They can take natural gas as an input. Efficiency can be increased significantly and with lesser CO_2 emissions than conventional electrical power plants by using Solid Oxide Fuel Cell (SOFC) [6].

SOFC technologies can be integrated with the PV system in a convenient approach in gas plants. In this regard, this study validates the possibility of gas plants being self-sufficient in electricity and be independent of the grid with the focus on the following specific points:

- To evaluate the technical feasibility of combining SOFC with PV in a natural gas processing plant.
- To assess the cost associated with SOFC-PV integration compared to a PV coupled with a battery backup.
- To compare two proposed solutions of PV-Battery Energy Storage System (PV-BESS) and PV-SOFC from an economic point of view.
- To develop a future scenario where PV integration with SOFC can be the solution to increase the power generation efficiency and better financial results compared to traditional power generation.

The integration of energy resources like PV system along with BESS and SOFC is being considered in many application due to its advantages over traditional energy generators from economic and environmental point of view [10].

2. Description of photovoltaic and electrochemical energy systems

With all the advantages known for solar power (clean, free source, competitive cost) [11], it still requires a back system to ensure continues availability of energy. Solar power requires an energy storage system to increase power plants' productivity and reliability. The large-scale system of batteries will be required as part of the PV solar system to allow a more significant share in the use of renewable energy and, at the same time, to stabilize the power supply via the grid. However, difficulties remain with large-scale battery units due to the extreme increase in associated costs and thermal management.

Obara and Morel [12] identify that some power generation companies in Japan have stopped investing in renewable energy to avoid the influence of renewable energy output changes. These companies have introduced the SOFC as part of the PV electrical power system, which can accommodate fluctuations in output from PV. Simultaneously, a combination of power generation from PV with SOFC and Gas Turbine can adjust the work in response to changes and avoid using batteries. It is suggested that the percentage of renewable energy usage is expected to increase with this solution [12]. The rate at which renewable energy is introduced into the electrical power system can improve. Additionally, the combined power generation system's power-generation efficiency will be more than 50% [12].

Two types of electrochemical devices can be used and combine with PV to ensure the availability of energy demand by the plant during the daily operation of the gas plant, the BESS and the SOFC.

2.1. Battery energy storage system

The BESS is expected to store solar electricity generated by the PV panels during the day time as part of the solar energy system. On the other hand, when PV panels do not produce electricity, the energy can be drawn from BESS, where the energy has been stored earlier. In case the system is connected to the grid, sending electricity back to the grid during daytime when the BESS is fully charged and will only draw electricity from the grid when the BESS is depleted. Meanwhile, the higher the BESS's capacity, the more solar energy it can store.

There are precise specifications when evaluating different BESS options, such as how much power it can provide (storage capacity) and what is the average amount of current it can release over a period of time (power ratings) in addition to depth of discharge and round-trip efficiency.

There are different types of BESS, and each one has its application and usage. Recently the lithium battery technology is being the most mature technology among other types like lead-acid batteries. Lithium-ion batteries are smaller and lighter than lead-acid batteries. They have the advantage of greater depth of discharge (DOD) [13,14] and extended life when compared to lead-acid batteries. Moreover, they seem to be the best BESS choice to backup power from solar panels.

2.2. Solid Oxide Fuel Cell

SOFC is an energy conversion system that uses gaseous fuel to generate electricity by an electrochemical reaction with the advantage of high energy efficiency and low emissions [15]. SOFC has a benefit and ability to operate directly on natural gas fuel.

SOFCs have many advantages, such as the simplicity of system configuration, utilization of several types of fuels, and operating at high-temperature with efficiency, reaching 70% in combined cases [16]. Several integration types are possible with SOFC either by internal reformer or external and can form a hybrid system with gas turbine [17,18]. Besides it can be an important solution for Micro-Grids power range by integrating with gas turbine [19].

SOFC is considered a strong applicant for power generation due to its low environmental impacts [20]. Additionally, it is the best option for distributed power systems, especially for places with high ecological constraints [20]. SOFC can deliver a different scale of power for commercial usage [21]. The environmental impact of SOFC has been highlighted by several research pieces, like Rillo et al. [22]. They performed a life cycle assessment study on different fuel types and found less CO2 emissions than traditional electrical generation systems. Besides, Lee et al. [23] confirm that environmental impact during the manufacturing stage is minimal.

As the integration of SOFC with renewable energy is another effective way of achieving higher energy efficiency conversion, one of the opportunities is the hybridization of PV power systems with SOFC. In this structure, renewable energy can work along with a natural gas-based system. SOFC is used to generate power, side-to-side the PV, and produce energy during nighttime instead of using battery storage as reported above. In this integrated system, the SOFC is designed to deliver the necessary power while the PV systems are inactive during the night or cloudy days in the daytime [24].

More details on SOFC, its uses, and usage difficulties in oil and gas operations can be found elsewhere [25].

3. Modeling and analysis

The plant's daily energy demand is one of the requirements to design the correct size of the PV system. For the case study, the gas plant requires to import additional power from the grid to meet the plant consumption requirement of 65 MW. This other daily demand differs from summer to winter and from day-to-night. The difference between winter and summer is mainly due to the higher HVAC load because of hot weather conditions. All fin-fan coolers are in operation in summer, and Air compressors' power consumption increases due to high ambient temperature.

The difference in demand between day and night is mainly due to the extra consumption of power related to lights and illumination during the night. The gas plant's hourly imported power demand is shown in Fig. 1 for the winter and summer seasons.

Since the difference between summer and winter demand (almost 4 MW) is very significant and corresponds to nearly 45% of the total required power, two cases are explored in this study, winter case and summer case. To design the PV plant and determine the necessary PV size, Touati's paper's data is used [26]. Fig. 2 illustrates Qatar's irradiance and the power generated from the solar PV during the winter and summer. The month of December is taken as a basis for this study for the remaining winter months (from November to April), while for summer, the month of June is taken as the basis for the summer case (from May to October) in this study.

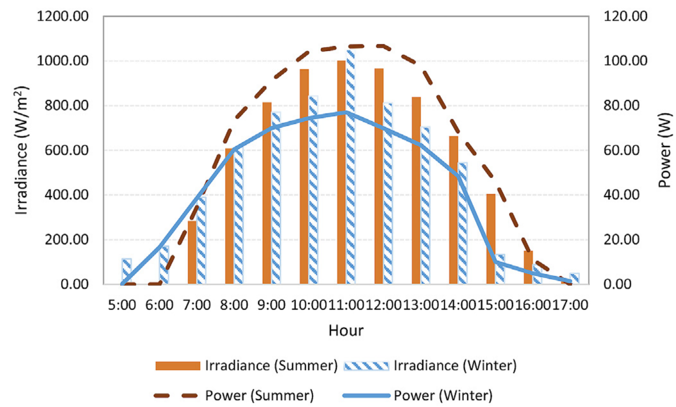

Fig. 2. Hourly irradiance and solar PV power production in Qatar.

The basis of PV design on peak demand is 9 MW in summer. It will also be based on the BESS case where extra energy must be stored during the day in summer to be used on summer nights where the demand is at its highest.

Since the plant power demand is highest in summer and night time, the PV solar system is designed in this study to provide 10 MW required power for the gas plant to be independent of the grid. The PV is sized at 33.5 MW, which is the peak solar power output at 11 a.m. in summer to meet the plant's peak demand. Since PV will operate only during the day time, The PV will be designed to provide the power for direct use by the plant for day time (e.g.8 h). Whereas at night, the backup system is proposed to provide the required demand (e.g.16 h).

For the sake of comparison between two electrochemical options and to have the PV package (specification and cost) the same for both cases, the PV is designed to meet BESS's requirements, and the same PV size will be used for SOFC. Note that the excess power from PV during the daytime for the SOFC case can be exported to the grid. Hence, this study's PV size is based on the peak demand during the year, and the amount of stored energy in BESS required for peak consumption during the year.

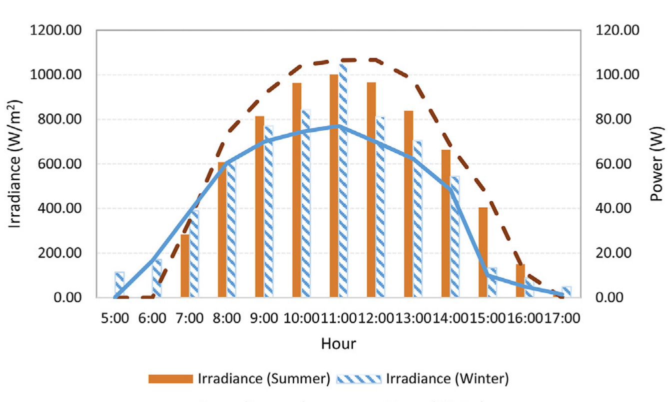

Fig. 1. Hourly imported power demand for the gas processing plant.

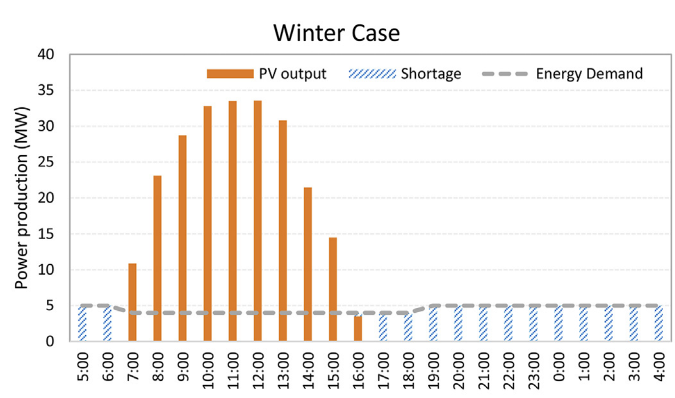

Fig. 3. Winter Case for PV power output and shortage.

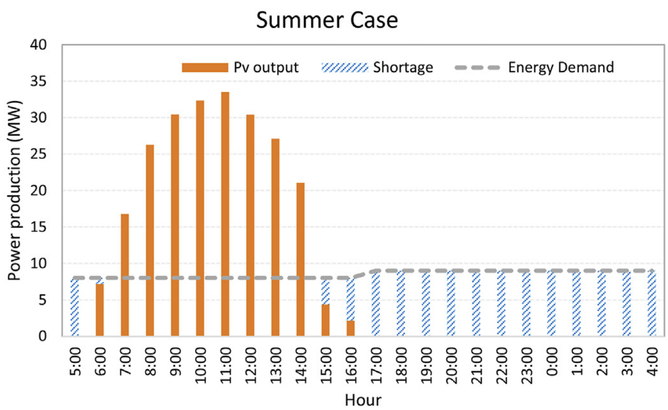

Fig. 4. Summer Case for PV power output and shortage.

Figs. 3 and 4 show the solar energy output compared to the demand in both summer and winter. In addition to the shortage of power when the sun is not available. During the year, these shortages of power will be filled by the proposed backup system, which is the subject of this evaluation and techno-economic study.

Since changing the PV capacity during each season is not practical, it will remain the same for all seasons. Whenever additional power is produced, it will mainly be in winter which will be considered extra energy to be exported to the grid. This will be the case of using BESS. However, for the possibility of SOFC, the additional energy from PV for storage will not be required since SOFC will be fueled by natural gas. PV will be only needed to provide the direct power demand during the 8 h in the day time.

Since the same PV configuration is assumed for both cases, any details on PV such as made, types, model, specification, cost, land space, and other related parameters will not be a part of this study. PV technical details will not impact the comparative conclusion of techno-economic for either case. The only figure required for the economic analyses related to the PV system is the total cost of the installed PV system, shown in Table 1.

The PV will be integrated either with BESS or with SOFC. The PV-BESS is a conventional system used in commercial and noncommercial projects. The PV-SOFC has been focusing on a new combination of renewable with fossil energy and a bridge to the new upcoming future. One of the assumptions made in this study for developing economic analysis is the commercial value of electricity produced by both cases. Even though the power produced will be used internally in the plant, an assumption is made that the produced energy will have a price similar to the tariff price. The detail tariff over the whole year is set by the electricity authority in Qatar for Industrial Bulk customers [28]. Table 2 demonstrates the tariff at different peak times throughout the year.

Even though the life expectancy of PV is assumed to be 25 years, according to the data from different published papers [29], the 25 years life of PV is somewhat challenging due to Qatar's harsh weather. Therefore, it will be covered in the sensitivity section of this study. A detailed explanation for both cases and techno-economic studies is made for each of these two cases below.

Table 1
PV parameters.

PV	Amount	Unit	Reference
Size	33.5	MW	
Efficiency	19	%	[26]
Unit Investment Cost	1.2	US$/W	[27]
Operation & Maintenance	2.5	% of TIC	[27]
Lifetime	25	Year	[27]

3.1. PV-BESS

Like the PV design size, the BESS capacity design is based on peak time during the summer. The required size of the energy storage will be 10 MW considering 10% degradation, which is the typical average degradation expected for such batteries. To cover the energy requirement for 16 h when the PV is inactive, the BESS will need to deliver 160 MWh of energy and maintain a minimum of 20% state of charge (SOC) in the battery all the time to prevent depletion. In addition to the 10% degradation, which will end to have BESS capacity at 210 MWh. Table 3 shows all the details concerning BESS specifications. Similarly, Fig. 5 indicates the setup of the PV-BESS case.

In the PV-BESS case, electricity is provided for 24 h for 365 days in a year. The summary for the 33.5 MW PV power plant in different states (charging and discharging) is shown in Table 4. The total cost of PV-BESS consists of the investment cost and both PV and BESS's operation cost. One of the emerging companies in lithium battery storage technology is Tesla. Their battery systems propose a smooth combination for solar PV systems, which is typical for off-grid projects where there is a need to be independent of the grid. The Tesla Power-Pack [27] is a solar electricity storage solution that ensures continuous power supply for 24 h. Table 5 shows the cost associated with BESS.

3.2. PV-SOFC

The SOFC is combined with PV running day and night to deliver the required amount of power in this configuration. The SOFC size is based on the peak demand, which is 9 MW plus degradation of 17%, to ensure the availability of 9 MW till the end of life. Hence, the SOFC for this case study is sized to be 11 MW. The SOFC unit requires running all the time since the startup and shutdown process is long and will reduce the fuel cell's life expectancy. During day time, the PV will provide the necessary power while the SOFC will be running on minimum fuel rate to keep it on hot standby mode, which will also deliver the capacity of about 1 MW. While in the night and when PV is inactive, the natural gas fuel to the SOFC unit will increase to generate the required demand. In such a PV-SOFC configuration, a 13 MW PV would be enough to provide the necessary power for consumers in the gas plant. However, the same size of PV (33.5 MW) will be used for the sake of fair comparison for this case. Fig. 6 shows the setup of the PV-SOFC case.

The fuel and air are required to be heated and pressurized to meet the SOFC stack requirement and to achieve that, the heat transfer from SOFC heat output is used to increase the fuel and air temperatures by introducing a heat exchanger. And small compressors are introduced to pressurize the air and fuel.

Using the chemical reactions and thermodynamic rules in addition to the data given in Appendix A in the supplementary information, the energy required for process reforming and SOFC output of power and heat can be identified. Table 6 shows the main parameters: the fuel, air, and water for a 1 MW power and 9 MW output of SOFC, the minimum and maximum power output based on time and season. During SOFC operation, only CO_2 is emitted, and almost no other harmful gases are emitted due to the system's high operating temperatures. If there are some, it is minimal and is negligible. The total GHG emissions for the PV-SOFC are only the flue gas outlet, which contains mainly CO_2.

Bloom energy is one of the manufactures of SOFC. Model ES-5700 [32] is chosen for this case study. Each unit of ES-5700 can deliver 200 kW, for which the details are provided in Table 7.

The cost of the PV-SOFC consists of the investment cost of PV

Table 2
Bulk Industrial Electricity tariff in Qatar.

Summer Period	Peak time (daily)	Applicable Rate daily – Peak Time (per kWh)
1st of May to 31st Oct.	12 Noon to 6 p.m.	32 Dirhams = **0.09 US$**
Summer Period	Off-Peak time (daily)	Applicable Rate daily – Off-Peak Time (per kWh)
1st of May to 31st Oct.	6 p.m. to 12 Noon	22 Dirhams = **0.06 US$**
Winter Period	All-day	Applicable Rate daily (per kWh)
1st of Nov. to 30th April	24 Hours	18 Dirhams = **0.05 US$**

Source: Kahramaa [28].

Table 3
BESS technical specifications.

Specifications of BESS	Value	Unit	Reference
Capacity	210	MWh	
Depth of Discharge	80	%	[27]
Storage efficiency	95	%	[27]
Discharge efficiency	95	%	[27]
Round-Trip efficiency	90	%	[27]
Full cycle	5000		[27]
Degradation	10	%	[30]
Dimensions[a]	1.3 × 0.82 x 2.18	m	[31]
Life Expectation	10	Years	[27]

[a] The dimension is for one 210 KWh unit.

plus its maintenance cost and SOFC's investment cost plus the operation and maintenance cost. The expenses related to SOFC in the PV-SOFC system are listed in Table 8.

Here, the cost of CO_2 represents the social cost of carbon, which is a measure of damage impact from one ton of carbon dioxide released in the atmosphere presented in dollar value.

The Levelized Cost of Electricity (LCOE) equation is:

$$\text{LOCE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{1}$$

Table 4
PV-BESS power arrangement.

	Winter	Summer	Unit
Charging	79	147	MWh/d
Discharging	76	140	MWh/d
Extra Energy	107	7	MWh/d

I is the investment expenditures; M is the operations and maintenance expenditures; F is the fuel expenditures if applicable; E is the electricity generation; r is the discount rate, n is the system's lifetime, and t is the year.

The LCOE is a cost related to a power source that evaluates and compares consistently different energy generation approaches. It is a commercial judgment and ratio of the cost to construct and operate an energy-generating system over that specific system's

Table 5
Economic inputs for BESS.

BESS	Amount	Unit	Reference
Investment cost	562	US$/Kwh	[27]
Civil cost	10	% of TIC	
Operation & Maintenance	1	Yearly % of TIC	[27]
Replacement cost	400	US$/kWh	[27]

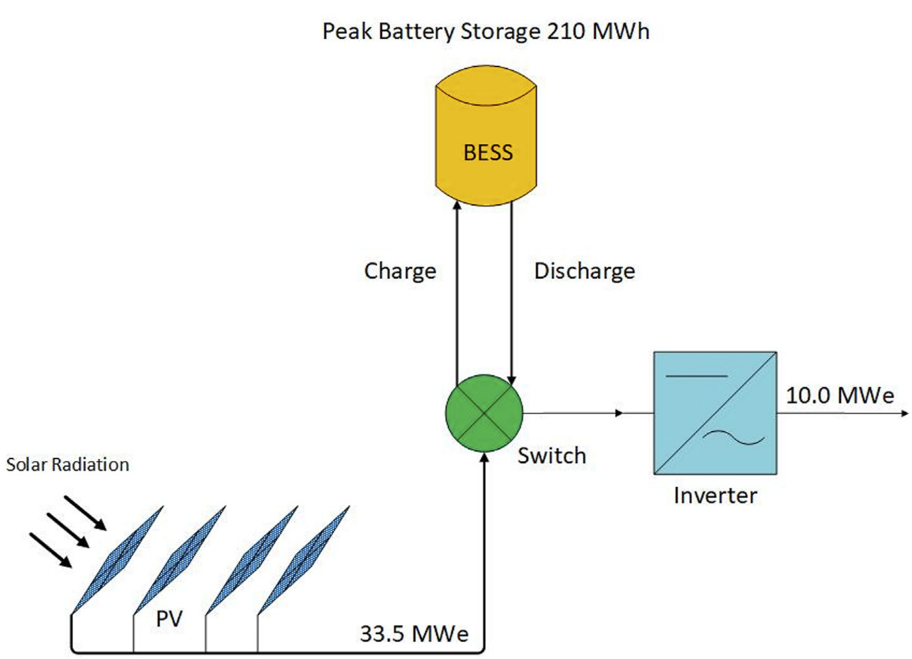

Fig. 5. Schematic drawing of PV-BESS case.

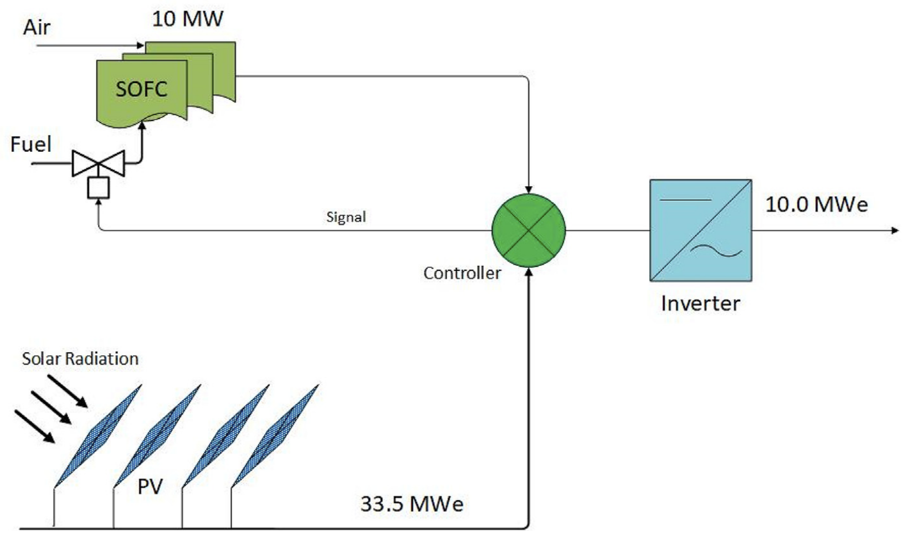

Fig. 6. Schematic drawing of PV-SOFC case.

Table 6
The fuel, air, and water rates for the PV-SOFC operation.

Material	SOFC Power Out	
	1 MW	9 MW
Fuel (kg/hr)	132	1188
Air (kg/hr)	2260	20,334
Water (kg/hr)	296	2667

Table 7
SOFC specifications.

Specs of SOFC	Value	Unit	Reference
Capacity	200	kW	
Quantity	55		
The ratio of fuel utilization	90	%	[33]
DC-to-AC converter efficiency	90	%	[34]
Dimensions[a]	4.54 × 2.68 x 2.13	m	[32]
Efficiency	53–65	%	[32]
Degradation	17.6	%	[35]
Life expectation	10	Year	[36,37]

[a] The dimension is for one 210 KW unit.

Table 8
SOFC economic parameters.

SOFC	Amount	Unit	Reference
Investment Cost	1.34	M US$/unit	[38]
	6700	$/kW	[38]
Civil cost	10	% of TIC	
Operation & Maintenance	6	Yearly % of TIC	[39]
Fuel cost	0.75	US $/MM kJ	[40]
Replacement cost	800	k US$/unit	
Cost of CO_2	30	US$/Ton	[41]

energy production during its lifetime. The LCOE can be expressed as the average minimum value where the electricity must be priced to achieve the break-even for that particular system over the project's lifetime. The LCOE is proposed as the main parameter in evaluating the economic analyses between the two cases.

4. Results

For 33.5 MW of power production from the PV power plant, the following graph in Fig. 7 shows average power production during the daytime in different seasons. The costs associated with the 33.5 MW PV system are detailed in Table 9.

4.1. PV-BESS

For PV-BESS to provide the energy all day during the year, Figs. 8 and 9 demonstrate the delivered power from PV plus the charge and discharge of BESS during winter and summer, respectively. In PV-BESS, there are no emissions emitted during the operation of this integration.

The financial results of the PV-BESS are shown in Table 10.

4.2. PV-SOFC

For PV-SOFC configuration, Table 11 shows the results and data for both day and night operations in the two seasons. Figs. 10 and 11 illustrate the production of power and fuel usage for 24 h in winter and summer, respectively, for the PV-SOFC system.

The GHG emissions result from using methane as fuel, and the total emissions are shown in Table 12. The annual emission of CO_2 is 15,385 Tons, and the yearly total cost of CO_2 will be 461,550 USD $.

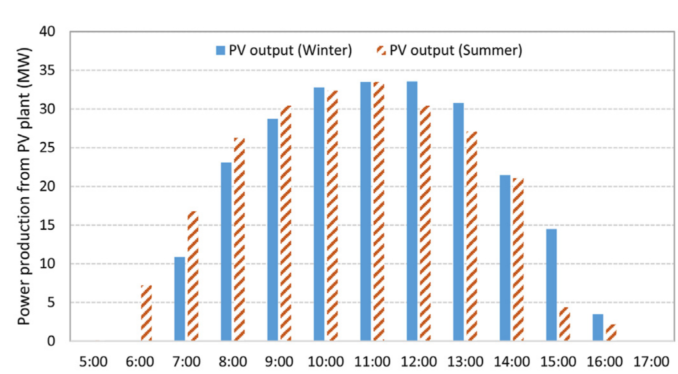

Fig. 7. PV output.

Table 9
PV economic parameters.

Parameter	Value	Unit
Lifetime	25	Years
Total investment cost	40.2	MUSD$
Annual O&M	1	MUSD$
Value at the end of life	0.151	MUSD$
Annual electricity	84,756	MWh

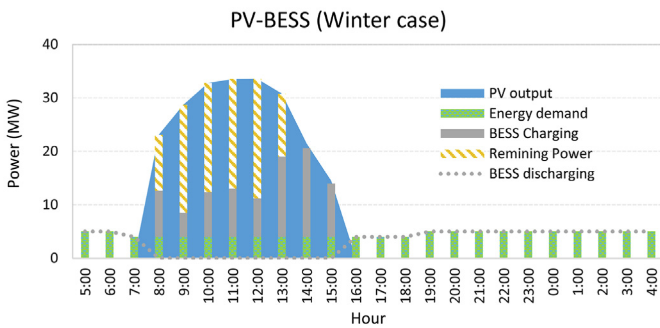

Fig. 8. PV Energy flow in winter.

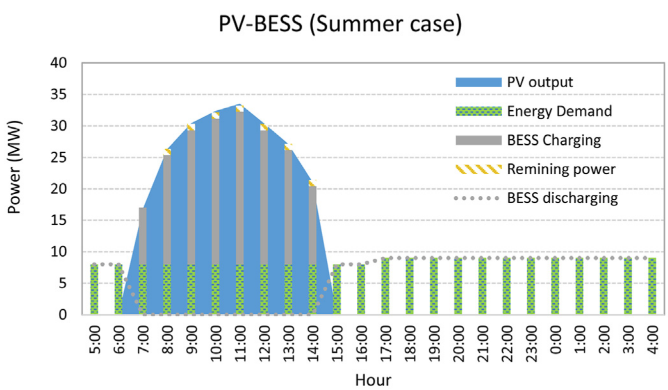

Fig. 9. PV Energy flow in summer.

Table 10
PV-BESS Economic parameters.

Parameter	PV-BESS	Unit
Lifetime	25	Year
Investment cost	170	MUSD$
Total cost	306	MUSD$
End of life value	12.7	MUSD$
DR	10	%
NPV	−230	MUSD$
ROI	0.05	
IRR	−10	%
LCOE	0.16	$/KWh

Table 11
Data result for SOFC operation in PV-SOFC.

Parameter	Value		Unit	Ref./Eq.
	Min. (1)	9	MW	
Fuel in anode	132	1188	kg/hr	
H_2 supplied to stack	66	597	kg/hr	Eq. (3)
H_2 utilized in stack	60	537	kg/hr	Table 8
Total energy out	1974	16,660	kW	Eq. (7)
DC power	1111	10,000	kW	Eq. (6)
Net AC power	1000	9000	kW	Table 6

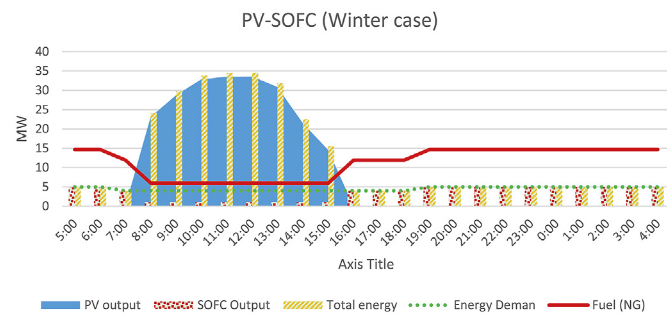

Fig. 10. Energy demand in winter by PV-SOFC

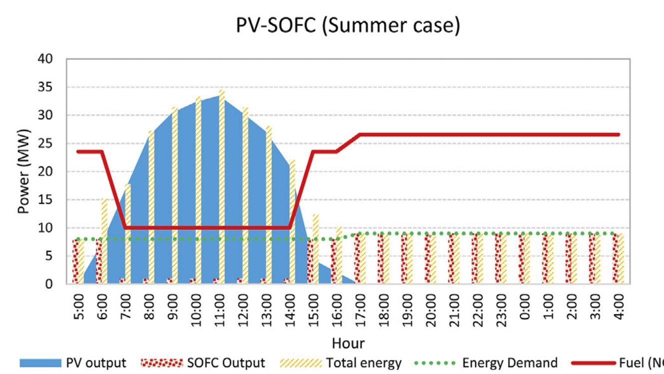

Fig. 11. Energy production in summer by PV-SOFC

Table 12
Daily GHG emissions by PV-SOFC.

Season	Emission CO_2 Eq. ton/day	Total Cost USD $/day
Winter	30.4	912
Summer	53.6	1607

The financial results of the PV-SOFC are listed in Table 13.

5. Discussion

The surplus power from PV in the PV-SOFC case for both seasons and PV-BESS in winter can be exported to the grid to assume the same price of the tariff as tabulated in Table 2. The other significant difference between the two cases is that for the PV-SOFC case, the GHG emissions (only CO_2) are emitted since the natural gas is used to generate power through SOFC. However, it is still cleaner compared to conventional combustion-based power generation systems. The cost of the CO_2 generated is included in the operation cost of the PV-SOFC system. The dimensions of BESS boxes and SOFC boxes are different where BESS requires much more space than SOFC, almost three times due to their lower energy densities. Additionally, additional construction work needs to be performed for PV-SOFC for natural gas lines and control systems. Since each case has its related additional costs, an assumption is made that each case seems to have almost the same expenses for these extra costs, and thus, not part of the discussion in this analysis.

Table 13
Economic results for the PV-SOFC.

Parameter	PV-SOFC	Unit
Life	25	year
Investment cost	121	MUSD$
Total cost	345	MUSD$
End of life value	12	MUSD$
Cost of CO_2	461	KUSD$/year
DR	10	%
NPV	−186	MUSD$
ROI	0.08	
IRR	−10	%
LCOE	0.11	$/KWh

5.1. Technical analysis

Fig. 12 shows the daily energy generated from both systems in different seasons. PV-SOFC generates more electricity in winter than summer, mainly due to access power output from PV and more energy than PV-BESS. In contrast, PV-BESS total energy generated in winter is a bit more than PV-SOFC electricity generated in summer. There is not much difference between total energy generated and energy consumed in the plant for the PV-BESS case for both seasons. However, there is a considerable difference between winter and summer for the PV-SOFC case for both total energies generated and energy consumed in the plant. This again for access power from PV. Almost no energy is exported to the grid for the PV-BESS case in summer because the whole system configuration is based on this peak period of demand. Table 14 shows the total energy generated annually for both cases in addition to the annual fuel quantity used by the PV-SOFC system and the CO_2, which is emitted from the PV-SOFC operation.

Using the PV-BESS instead of the PV-SOFC to cover the demand of 9 MW, a saving of only 15,385 tons of CO_2 is possible annually, which will contribute to only 385 thousand tons of CO_2 for the 25 years of a typical gas plant. Thus, the PV-BESS will have a lower environmental impact from the environmental point of view than the PV-SOFC during operation.

5.2. Economic analysis

As seen in Fig. 13, PV-SOFC has lower investment costs than PV-BESS, mainly due to the battery energy storage system's high cost. However, the total cost for PV-SOFC over the lifetime of the project is more elevated than PV-BESS. This is mainly due to the operation and maintenance cost of SOFC, in addition to fuel and CO_2 cost, which is being added to the total cost of PV-SOFC. Nevertheless,

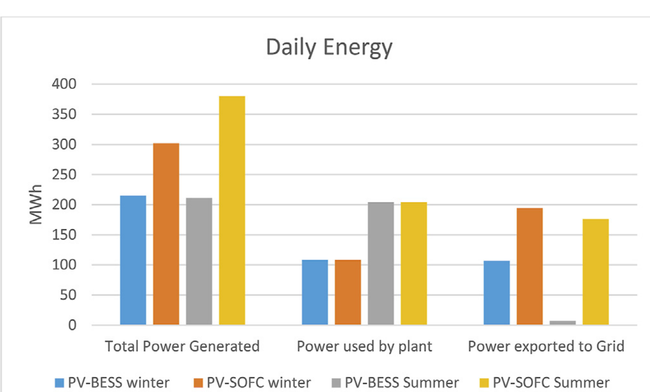

Fig. 12. Energy flows of both systems in both seasons.

Table 14
Summary of the technical analysis results.

	PV-BESS	PV-SOFC	Units
Annual Energy Production	77,770	124,654	MWh
Annual Fuel Consumption	–	2.97E+11	kJ
Annual Emissions (CO_2 eq.)	–	15,385	Tons

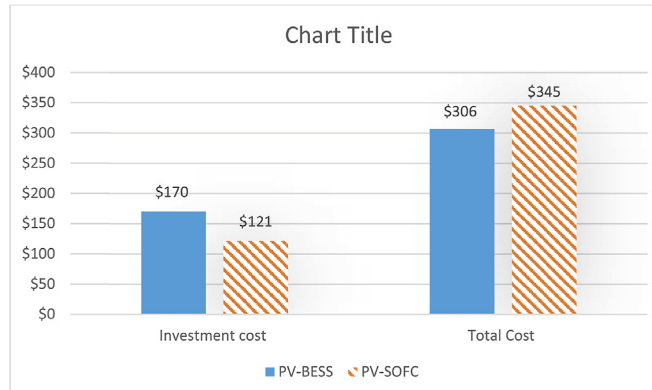

Fig. 13. Cost of investment and total cost for both cases.

both systems with a 20% depreciation have almost the same value of 12 M USD$ at the end of 25 years' lifetime.

Table 15 summarizes the financial results of both cases where for a typical life of 25 years, both systems show negative NPV, which is an indication of losses, but the PV-SOFC has a better NPV than PV-BESS. Moreover, these figures are based on the price listed in Table 2.

Also, the internal rate of return is negative in both cases. IRR at almost −10% for both cases means the investment, in this case, is losing money at a rate of 10%. The return of investment is in favor of the PV-SOFC system. The Return of Investment (ROI) is a performance measurement to assess investment satisfaction between both cases. The PV-SOFC results in better ROI, which shows better investment gains favorably to its cost.

The Levelized Cost of Electricity is 0.16 $/KWh in the PV-BESS case, while it is 0.11 $/kWh in the PV-SOFC system. This difference of 5 US cents per kWh between them is in favor of PV-SOFC. For the project's lifetime, this will end up saving around 70 M USD $ for the total demand if PV-SOFC is employed rather than PV-BESS in such a gas plant.

5.3. Sensitivity analysis

The life expectancy of 25 years for PV is challenging in the Middle East region, mainly due to the harsh weather during the

Table 15
Summary of the economic analysis.

Parameter	PV-BESS	PV-SOFC	Unit
Lifetime	25	25	year
Investment cost	170	121	MUSD$
Total cost	306	345	MUSD$
End of life value	12.7	12	MUSD$
DR	10	10	%
NPV	−230	−186	MUSD$
ROI	0.05	0.08	
IRR	−10	−10	%
LCOE	0.16	0.11	USD$/KWh

summer. According to Ref. [25], the PV seems to be losing its efficiency significantly after 15 or 20 years. Therefore, if we assume PV life will be only for 15 years, then the PVs must be replaced. This applies only for PV-BESS but is not required for the PV-SOFC case since only 13 MW PV is enough for the PV-SOFC case. Hence, losing PV efficiency to less than 50% for the remaining life of the PV-SOFC system is still acceptable.

Another interesting point is the replacement of the BESS or SOFC every ten years. According to Perkins [27], the replacement for BESS is suggested only for 50% of the plant every ten years. A similar approach can be made for SOFC since the SOFC is sized for 10 MW. Additionally, the demand at wintertime is maxed at 5 MW, then 50% of SOFC units can be switched off during the winter season, which is six months, which will extend the SOFC life. This means that only 25 units are running six months per year, and the remaining 25 units are switched off. With such an approach, the replacement every ten years of SOFC will be only for 50%, which will improve the NPV from −185 to be −140 M USD$ compared to −220 MUSD$ for PV-BESS case.

One of the changing parameters in PV-SOFC is the natural gas price, which is not fixed and can change over time based on oil and gas markets. The financial results of PV-SOFC seem to be impacted while the PV-BESS is independent of gas prices. Fig. 14 shows that at 24 $ per MMBtu of natural gas, which is equivalent to 1.05 million kJ, the LCOE of the PV-SOFC system will be equal to the LCOE of the PV-BESS system, and any price higher than 24 $ per MM kJ will result in a higher LCOE for PV-SOFC compared to PV-BESS.

5.4. Projected scenario

Many researchers and market analysts believe that the price of new technologies like SOFC and BESS will drop soon due to new regulations in place, improvements in material specs used, and bulk production of these technologies. Assuming a 50% drop in BESS and SOFC prices, Table 16 shows the new projected price for different items and materials. With the above inputs and a discount rate of 5%, new economic parameters for both cases can be found in Table 17. It is evident that the NPV for PV-SOFC is positive, and it is 5 million USD$, and the IRR is 4%. While these PV-BESS parameters still show negative values, which indicate that PV-SOFC has a better chance commercially in the future than PV-BESS. Another point in this scenario, as seen in Fig. 15, is the LCOE for PV-SOFC, it is not only less than the LCOE of PV-BESS, but it is less than the minimum tariff set by the authority for the bulk industries. The LCOE of PV-SOFC at 4 cents per kWh is achievable if the cost of SOFC drops to 50%, which the manufacturer needs to reduce the capital cost and ensure production in bulk.

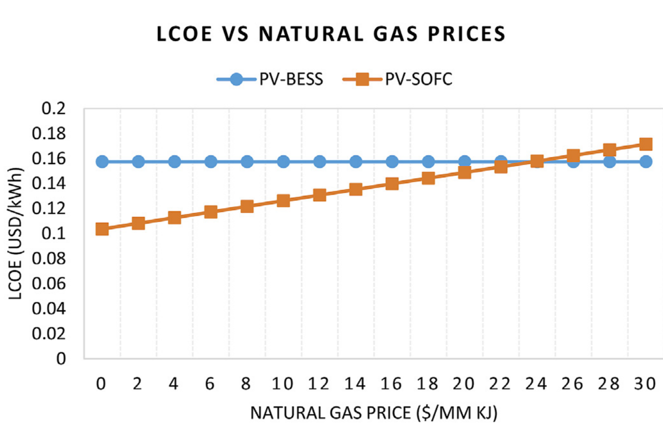

Fig. 14. LCOE of PV –SOFC and PV-BESS at different natural gas prices.

Table 16
Projected price with 50% off.

Item	Cost	Unit
PV	600	$/kW
BESS	281	$/kWh
SOFC	670,000	$/200 kW
NG price	0.75	$/MM kJ
CO2	10	$/Ton
O&M	3%	of TIC

Table 17
Economic parameters for the projected scenario.

Parameter	PV-BESS	PV-SOFC	Unit
NPV	−77	5	MUSD$
ROI	0.21	0.9	
IRR	−4	4	%
LCOE	0.08	0.04	USD$/KWh

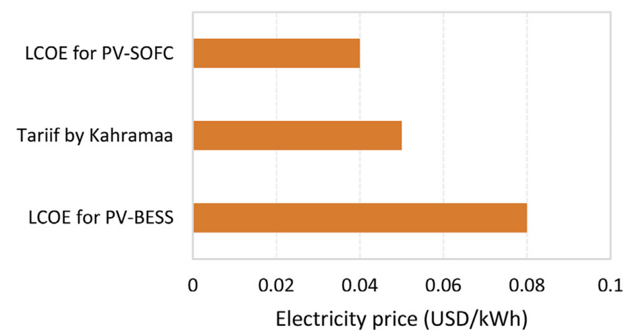

Fig. 15. Comparison of LCOE with the existing electricity tariff.

6. Conclusions

This study investigates the potential for and demonstrates a more efficient and cleaner conversion of natural gas into electricity using SOFC integrated with PV solar system in gas processing plants. With all other benefits such as higher efficiency, more availability, and better reliability, the PV-SOFC is economically better than PV-BESS based on the LCOE. The LCOE for PV-SOFC is 0.11 US$ per kWh, while it is 0.16 US$/kWh for PV-BESS. Moreover, in the projected scenario, the LCOE of PV-SOFC is at 0.04 USD$ per kWh, which is less than the tariff set by the power authority for bulk industries. Furthermore, PV-SOFC has a positive NPV of 5 million US$ with an internal rate of return at a rate of 4%. The significant outcomes of this study are summarized as follows:

- The overall system availability of the PV-SOFC system is better than the PV-BESS system.
- The LCOE is less for PV-SOFC compared to that of PV-BESS.
- With the future reduction in the capital cost of SOFC, the PV-SOFC stands as a formidable solution to cover the shortage in demand, which will reduce the operational cost due to electricity import.
- There is a potential opportunity to generate all the necessary power for a typical gas processing plant from a sizeable PV-SOFC system. It can run independently from the grid.

The integration of SOFC systems in oil & gas operations offers the desired solution to clean and efficient operations. Eventually, enabling effective integration and smarter employment of SOFC systems at different scales and configurations may improve overall system efficiency.

The successful integration and cost-effective outcome of the integration of renewable energy with a fossil fuel-based SOFC are feasible for natural gas processing plants or to a specific geographical location. However, it can succeed elsewhere where PV can function appropriately with availability and low natural gas price. Many applications, like distributed energy resources, can benefit from PV-SOFC integration.

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Intellectual property

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

Research ethics

We further confirm that any aspect of the work covered in this manuscript has been conducted with ethical.

Authorship

We confirm that the manuscript has been read and approved by all named authors.

We confirm that the order of authors listed in the manuscript has been approved by all named authors.

Declaration of competing interest

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

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Nomenclature

$\dot{Q}_R$	The heat required for reforming
$\dot{m}_{H_2}$	The mass flow rate of H_2
$\dot{m}_{in,water}$	The mass flow rate of water to the reformer in SOFC
$\dot{m}_{out,water}$	The mass flow rate of water out from SOFC
MW_{H_2}	Molecular Weight of H_2
MW_{H_2O}	Molecular Weight of H_2O
U_f	fuel utilization ratio
$E_{SOFCout}$	Total Energy out from SOFC
U_{H2}	Hydrogen utilized in a stack
ΔG	Change in Gibbs free energy
ΔH	Change of enthalpy
°C	Degree Celsius
AC	Alternative current
bar	a unit measurement of pressure
c	Charge of cell
CCS	Carbon Capture and Sequestration
CH_4	Methane
CO_2	Carbone Dioxide
DC	Direct current
DoD	Depth of Charge
DR	Discount rate
EES	Engineering Equation Solution (software program)
F	Faraday Constant
GHG	Greenhouse gases
h	Enthalpy
H_2	Hydrogen
I	Current
IRR	Internal Rate of return
NG	Natural Gas
Ne	Number of Electron released
NPV	Net Present Value
O&M	Operation & Maintenance
O_2	Oxygen
P	Power
ROI	Return of Investment
SCF	Standard Cubic Feet
SOFC	Solid Oxide Full Cell
V	Voltage

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.119923.

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