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Techno-Economic Assessment of Power Supply in Offshore Platforms by Renewable and Conventional Sources

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ABSTRACT

The economics of two different power generation systems for an offshore complex installed in the Persian Gulf is considered. The base case defines the present condition in which the total power demand of the complex is supplied by burning the associated natural gas extracted from the platform on board in its thermal power plant. The purposed scenario considers a wind farm located near Bardekhun in Bushehr province to be connected to the complex power network and shares its power generated by renewable resources with the platform. The average wind speed and the wind turbine power generation are considered to have uncertainty. Thus, Monte Carlo simulation (MCS) is used to consider the uncertainties in the average wind speed and the wind turbine power generation. The purposed scenario is found obviously more beneficial with some conservative assumptions. The results show an about 30% reduction in pollution and a profit of $3 million in a year.

1. Introduction

A challenge in offshore oil and gas operations is how to obtain a cost-effective, reliable, and steady power supply at a remote location in the ocean where the power grid is not easily accessible due to the high cost and challenge of extending power cables into the ocean environment over hundreds of kilometers. Currently, the offshore power production is largely based on the use of gas or diesel turbines with quite low efficiency (~20–25 %) (Baringbing et al., 2011). Mounting diesel or gas turbine generators on platforms or barges introduce its own issues as a typical solution. These generators are difficult to maintain and operate at sea. Diesel generators must be refueled frequently, requiring costly logistics such as ship trips. Gas turbine generators also burn fuel gas produced from the platform, which could be exported and make revenue. The cost of the fuel itself is extravagant, especially for long-term operations. Further, diesel generators emit CO_2 which can affect operations via environmental regulations (Mekhiche and Kathleen, 2014). As an example of Norway, continuous burning of these conventional fuels in offshore generators will generate about 80% of the total CO_2 and NO_x emissions from the Norwegian offshore

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installations. Thus, offshore platforms are facing difficulties in terms of operating their activities in an environmental manner (Tiong et al., 2015).

Recently, growing global tendency to eliminate or lower emissions by the application of green power generation methods has caused newer and less ecologically harmful technologies to be developed in order to generate power not only in a renewable but also pollution-free way for offshore platforms (Zahari and Dol, 2014). There are lots of valuable studies conducted concerning similar subjects in 2017. Some assess the renewable potentials, and others investigate the possible integration methods. The potentials of the wind of Chile are studied in comparative terms of levelized cost of energy and rate of return (Mattar and Guzmán-ibarra, 2017). In another work, the inherent variability and forecasts of the wind are considered in order to enhance the estimations of renewable power generation and its costs for south-west Portugal (Pacheco et al., 2017). The modeling of the integration of variable renewable energy-based power supply in Europe demonstrates that the use of storage and grid can keep the reductions in power supply below 20% of the demand for theoretical variable renewable energy shares of up to100% (Gils et al., 2017).

Generally, there are plenty of studies done in the field of obtaining renewable energies from stochastic natural energy potentials, optimizing the energy absorbing modules for offshore and onshore environments, and integrating harvested green energies with conventional energy systems worldwide. Among these, only a few are concerned with the energy system of an offshore oil and gas platform. There are some other studies focusing on the processes associated with this type of platforms aiming to obtain the energy efficiency and optimization hints to achieve more economic and efficient operations.

As the present study seeks the availability and integrability of the inherently stochastic offshore renewable energies to supply the maximum possible demand of an offshore oil and gas platform located in the Persian Gulf, a vast number of available relevant works have to be categorized in a way appropriate to the subject of this study. There are three main categories of relevant research: those related to the renewable energy absorbing means; those concerning the offshore platform conventional energy system and energy assessment; and those introducing hybrid energy systems containing offshore environmental potentials and the as-built onboard energy generation systems of the platform.

Offshore renewable energy conversion platforms-coordination action (ORECCA) reported the inventory of the state of the art of current renewable energy converters and platform technologies as they are being used in the oil and gas industry, the offshore wind energy industry, and the ocean energy, that is, the wave and tidal energy as well as a benchmark among different technologies on the basis of the experience of the partners of their projects. This report developed the criteria to identify the benefits and limitations of each type of structure, as well as the applicability of the structures for offshore renewable technologies in a comparative study (Vannuci, 2011).

The application of various sources of alternative energy were discussed in 2014. The energy potentials of wind, wave, and solar were discussed to assist with powering of offshore oil platforms particularly the one located in north-west shelf of Australia. Also, the optimization of feature selections was performed before choosing the most suitable device for each energy resource. By comparing the capital cost required for each type of commercial energy converters, the most suitable option was introduced. As a result, for the considered platform demanding 30 MW power, the available options were utilizing various wave energy converters (WECs), including 40 units of Pelamis, 35 units of PowerBouy, and 86 units of Wave dragon with a rated power capacity of each unit equal to 750, 866, and 350 kW respectively and with a capital cost of 1.2–1.8 million USD if wave energy alone was considered to supply the whole platform. Using 15 units of Vestas V80-2MW with a capital cost of 2 million USD was the best solution among other offshore wind turbines if wind energy was taken into account alone. It was also mentioned that the solar energy source is not a good choice for powering offshore platform due to the high cost of installation and maintenance (Hj Mohd Amin, 2014). The inherent stochastic nature of the wind and wave energy and any composite configuration of the available renewable energy converters in the outcomes of the total generated power in the study have not been considered.

Moreover, a methodology was established to calculate the cost of a floating offshore wind farm. The methodology was used to demonstrate that the total cost of a floating offshore wind farm varies depending on the type of floating platform and the geography of the location. Moreover, the overall cost was found to be higher for far-shore areas (Wolanski et al., 2015). The possibility of lowering the costs by connecting the wind farm to nearby offshore oil and gas platforms which can be grid-connected was not considered in the methodology introduced.

Three innovative ideas for the exploitation of offshore wind energy were explored in 2006 (Barrera Limón, 2006). The ideas consist of three possible configurations of the wind farm and grid connection: offshore wind farm to the mainland grid, offshore wind farm to an offshore oil rig, and offshore wind farm to the mainland grid via an offshore oil rig. The objective of that study was to analyze the cost-benefit of these three configurations in order to know whether they are economically viable for realization. Furthermore, if viable, what advantages they offer over the common connection realized nowadays. The analyses showed that when the offshore wind farm is connected to an oil rig, the energy utilized will further decrease to 0.80, which has to deal not only with the losses during transmission but also with the utilization factor which reflects the energy not utilized by the oil rig when its demand is under the supply. When the configuration involves the offshore wind farm connected to the grid via an oil rig, the energy utilized can be improved to 0.91. The improvement is caused by the availability of two receptors: the oil rig and the grid. The energy can be first utilized in the closer oil rig with fewer losses and the surplus is delivered to the grid; therefore, the entire energy output can always be used. Regarding the energy demand of the oil rig, the potential wind farm energy output is able to cover 45% of it for the studied cases. Thus, the study ranked the connection from the offshore wind farm to an oil rig as the best supported by much reduced initial investment and low losses when the oil rig is closer. Further improvement can be achieved using a wind speed time series with higher resolution and incorporating the hourly energy demand pattern of an offshore oil rig. More constraints can be included to improve accuracy of especially the operation characteristics of the natural gas turbine system and the limitations it may have when coupled to the offshore wind farm in the power supply.

Another study reported present ideas of combined wind power and combustion-based power system for offshore oil and gas installations and presented the challenges related to two types of concepts: a stand-alone system and a grid-connected system. The study also recommended an alternative approach which was to use offshore wind turbines installed close to the oil and gas installations can be combined with gas/diesel turbines, and can operate in an island mode without the need for the cable connection to the shore. The report indicated that an interconnection between the offshore wind farms, the oil and gas platforms, and the onshore grid can result in reduced operating costs, increased reliability, and reduced CO_2 emissions (Baringbing et al., 2011). In spite of all the mentioned advantageous, that kind of hybrid power systems may have problems when integrating a thousand megawatts of wind power produced in a stochastic behavior due to natural wind fluctuations. The rapid power fluctuations from the large-scale wind farms introduce several challenges to reliable operation and contribute to deviation in the planned power generation, which may lead to power system control problems. The control problem is solved by de-coupling the electric power conversion directly from the wind turbines, as was recommended in the work of Baringbing et al.(2011).

There is an important principle difference between the offshore wind industry and the offshore oil and gas industry. The offshore oil and gas industry consists of uniquely designed installations. Meanwhile, the offshore wind installation will require multiple installations of identical machines. Cost effective multiple installations will require a degree of innovation which is not required in the oil and gas industry because each installation is unique.

A dynamic hypothetical power system was simulated in a study on the North Sea in order to investigate whether the system configuration was a feasible way to integrate offshore wind power and oil and gas platforms to the onshore power grid. The results of the simulations indicated that the system configuration reviewed therein represents a feasible way to integrate oil and gas platforms and offshore wind power with the onshore power grid. The simulation results showed that the developed control system was able to keep the voltage and frequency variations within the grid code in IEC 61892 even during large disturbances. The study concluded that the system handles variations in the load very well and that the system configuration studied was regarded as a feasible way of integrating oil and gas platforms and offshore wind power with the onshore grid (Kolstad et al., 2014).

Another study explored the technical feasibility of utilizing an offshore wind farm as a supplementary power source to a number of electrical grids of offshore oil and gas platforms and providing surplus power to an onshore grid. The study considered three case studies comprising wind farms rated at 20, 100, and 1000 MW with the focus on the operation benefits of CO_2/NO_x emission reduction, the electrical grid stability, and the technical implementation feasibility. One yearly case based on the real load data gave an annual reduction of

40% of the CO_2/NO_x emissions (He et al., 2013). All the three cases were theoretically feasible based on that preliminary study; further studies are required to overcome many other operational, logistical, and economic problems.

Hence, there is a need for other complementary studies in order to investigate the stochastic nature of those mentioned renewable energy sources and the availability of the power for any specific particular application, as well as the possibility of lowering energy costs for any power generation system if it is connected to a stochastic renewable energy generation source.

This study aims to find the possible solutions for reducing the cost and consequences of old power generation systems such as their environmental emission production. The solution appears to be found in designing of new power generation systems. The present study reviews the solution for the integration of old power systems with renewable power plants for offshore oil and gas platforms.

As offshore oil and gas platforms are widely different in their design and engineering, it is difficult to choose one as the general case platform to be compared with new systems in terms of technical and economic aspects. By the way, there are some key specifications which are considered to be assigned to the case platform. A thermal power plant system capable of providing the maximum amount of power required for the processes on board has to be designed and mounted on it. There should also be facilities designed for exporting natural gas from the platform (in case of an oil platform). The platform is considered to have facilities to establish a connection to the shore grid or nearby electricity grids via sub-sea cables. Regarding the problems of the availability of required data, an offshore complex located in the Persian Gulf having all the mentioned conditions is considered to be the base case of the present study.

2. Methodology

The aim of this study is to statistically simulate the performance of an innovative power generation system which is a combination of the old power generation unit on the platform and a wind farm and to compare the outcomes concerning the emissions and energy costs of the platform. This is performed by using the wind data collected from the nearest wind station to the offshore complex, by generating the wind speed logs in time, by converting its kinetic energy potential to electrical power via wind turbines, and by comparing the cost and benefits of this power generation method with the old one.

Generally, there are two common distributions used for wind speed: Rayleigh and Weibull distributions. In the present study, the wind speed distribution is generated using the statistical mean and standard deviation values and applying Weibull distribution assumption, which is being widely used for wind speed applications. Available wind speed measurements at the considered wind station are being taken at the height of 40 m, while it is necessary to find the wind speed at the selected turbine's hub height for wind energy assessment. The wind speed profile can be transferred into the desired height using Eq. (1). Eqs. (2) and (3) calculate the surface roughness and the wave length respectively (Amirinia et al., 2016):

$$\frac{U(z)}{U_{ref}} = \frac{\ln(Z/Z_0)}{\ln(Z_{ref}/Z_0)} \tag{1}$$

$$\frac{Z_0}{H_s} = 1200\left(\frac{H_s}{L_p}\right)^{4.5} \tag{2}$$

$$L \cong \frac{g}{2\pi}T^2 \cong 1.56T^2 \tag{3}$$

After obtaining the distribution of the wind speed at the desired height, the specifications of the subject wind turbine are being considered. These specifications consist of its power curve, cut-in and cut-off speeds, rated power, rated speed, and its hub height from the base. The mean annual wind turbine power can then be calculated. Eq. (4) shows the calculations of the probability and accumulated probability for the wind speed distribution. Also, the mean annual power production for a wind turbine with a specific power curve can be calculated using Eq. (5).

$$p(U) = \left(\frac{k}{c}\right)\left(\frac{U}{c}\right)^{k-1} \exp\left[-\left(\frac{U}{c}\right)^{k}\right]$$

$$F(U) = 1 - \exp\left[-\left(\frac{U}{c}\right)^{k}\right] \tag{4}$$

$$k = \left(\frac{\sigma_U}{U}\right)^{-1.086}, \quad \frac{c}{U} = \frac{k^{2.6674}}{0.184 + 0.816k^{2.73855}}$$

$$\overline{P_w} \times 365 \times 24 \int_0^{\infty} p(U) P_w(U)\, dU \tag{5}$$

From the available data on a similar platform, designed by SHELL, and by considering a year in hours, the full load (100%) represents 2/3 of the time (5840 h), and both the medium load (70%) and the minimum load

(50%) represent 1/6 of the time (1460 h) (Barrera Limón, 2006). The considered scheduled daily normal consumption is as follows: 24–10 h 100% load, 11–14 h 70% load, 15–19 h 100% load, and 20–23 h 50% load. The energy efficiency of the natural gas turbine system is assumed to be 20%.

This study assumes that the average satisfactory numbers of required wind turbines are such that their total annual average power generation will be equal to the annual average demand of the platform. Following the mentioned conditions, the minimum wind farm scale is estimated. Regarding the power curve of the applied wind turbine and the wind speed probabilities, total available power production from the wind farm is calculated. By comparing the platform demand and the wind farm power in each month, the amount of excess or loss of the green power relative to the total monthly demand is then calculated. In the cases which the green generated power is less than the platform demand, a counter parameter counts a monthly power shortage for the platform. This parameter is then used to calculate the probability of power shortage in each month. The amount of power shortage in those months is being considered to be supplied by burning natural gas in the gas turbines. Also, the amount of the natural gas being saved in the other case is considered to be exported for making money. Moreover, if the option of storing power in storage facilities such as high capacity batteries, natural grid, etc. was available, it would be taken into account in the cases which the excess power generated in a month compensates for the losses in others. This available power difference can be stored in order to be used for months in which the wind power is less than the platform demand. The described methodology is being repeated for a certain number of times. The uncertainties of the wind monthly average and the turbine power at each wind speed are considered. The probabilities of power shortage are being calculated using a Monte Carlo simulation method. In order to consider the uncertainty of the wind speed, which is an inherently stochastic parameter, the monthly wind speed averages are being generated for 104 times, and in the case of each one, the wind turbine power is being estimated for 103 times in order to consider the uncertainty of the wind turbines. This study considers all wind farm turbines to be manufactured under similar conditions having exactly the same power outputs. Figure 1 shows the flowchart of the methodology established in this study.

As shown in Figure 1, the methodology flow chart includes three levels. The first level of the chart depends on the selection of the offshore platform, wind farm location, and wind turbines to be applied. The average wind farm scale is then being estimated at the second level considering capacities assigned in the previous level. Finally, the Monte Carlo simulations are being generated at the last level, assuming the related uncertainties. The probabilities of wind farm monthly power shortage and the average costs and benefits of the proposed power generation method is then being calculated and compared with the present scenario.

3. Case Study

An offshore complex in the Persian Gulf is considered as the case of the comparison. The platform is located 85 km away from the southwest of Kharg Island in the Persian Gulf. As shown in Figure 2, this complex contains five different category platforms: two production platforms (SPP-1 and SPP-2), two wellhead platforms (SWP-1 and SWP-2), and one living quarter (SLQ) in addition to a floating storage unit (FSU).

The production facilities of this field (SPP-1 and SPP-2) will allow the treatment of the produced crude oil to fulfill export specifications prior to being transferred to the FSU. SPP-2 is a dedicated platform for the final processing of the crude oil coming from nearby fields and exporting to the storage facility. The crude is processed on its dedicated platform, SPP-1. The complex is equipped with a thermal plant consisting of natural gas turbine generators (NGT) (three sets, each one 13.07 MW) which are designed in a way to supply the total estimated platform electricity and process heating demands under both normal and peak load conditions. Load conditions are forecasted from the primary relevant reservoir studies and analyses. This demand is supplied by burning associated extracted natural gas from the field itself and diesel in the case of emergencies. There are two different electricity switchboards designed for the platform electricity network: high load (11 kV) and normal load (400 V) switchboards. There is another 400 V switchboard installed on the platforms as the emergency switchboard that is directly connected to diesel generators to take responsibility of the power supply and distribution in the case of emergencies in order not to shut down the critically essential machinery or processes on the platforms. Table 1 lists the demand details under both normal and peak load conditions for each platform.

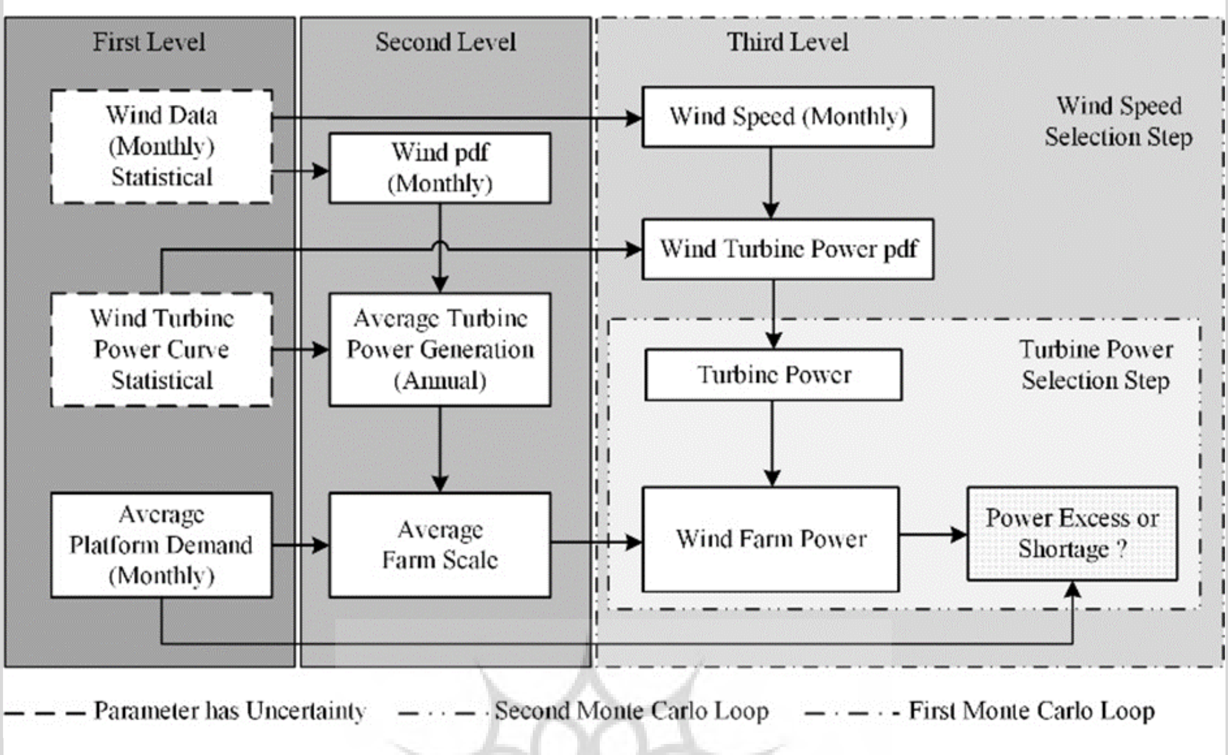

Figure 1. Methodology flow chart.

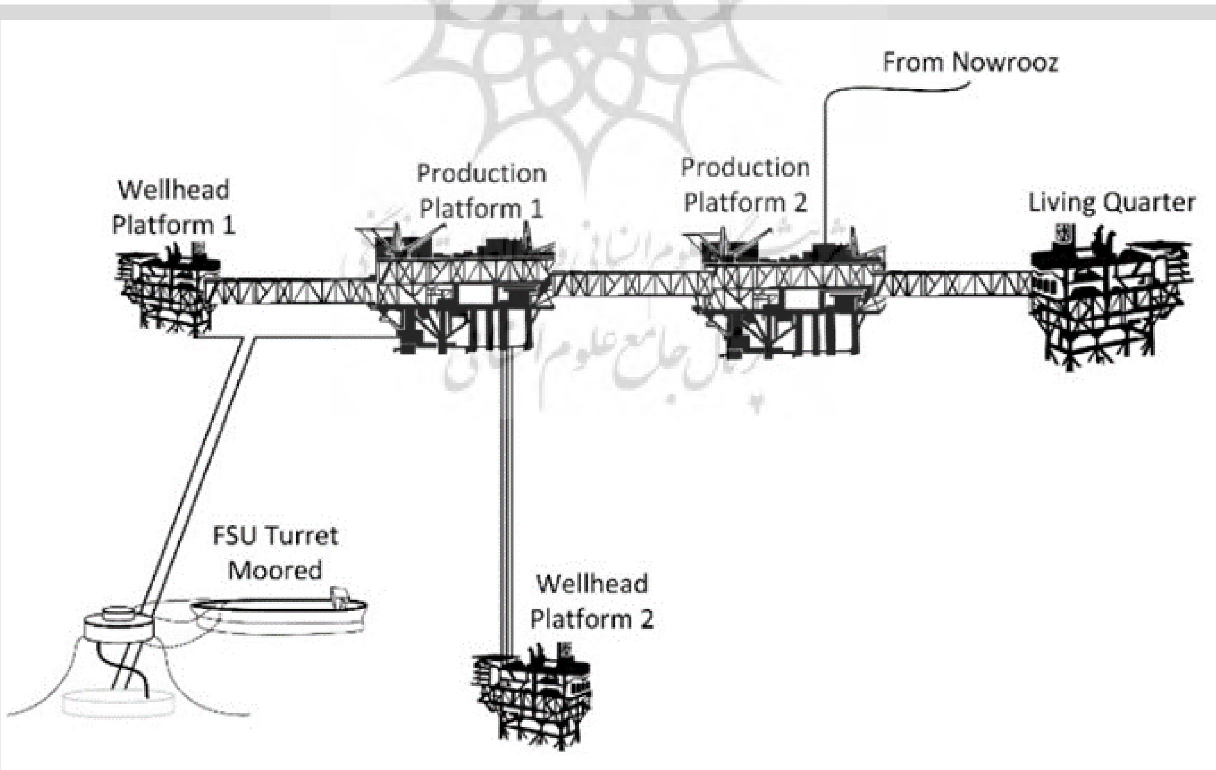

Figure 2. Case study offshore complex.

Table 1. Details of the offshore platform demand under normal and peak load conditions.

		Normal			Peak		
Name	V	kW	kVAr	kVA	kW	kVAr	kVA
SPP 1	11k	21993	14133	26142	22720	14521	26964
	400	1264	1094	1672	1366	1154	1788
	400	662	415	781	695	435	820
SWP 1	400	60	35	69	68	40	79
	400	16	8	18	18	10	21
SWP 2	11k	1697	1692	2396	1706	1698	2407
	400	93	57	109	102	63	120
SLQ	400	938	545	1085	963	561	1114
	400	269	169	317	285	179	336
SPP 2	11k	4406	2916	5284	4600	3032	5509
	400	910	870	1259	969	904	1325
	400	139	87	164	145	91	171
Total Demand		**32447**	**22021**	**39296**	**33637**	**22688**	**40654**

The offshore complex power generation system with its design condition is considered as the base case. The cost of energy for this scenario is the trading cost of burnt natural gas in onboard gas turbines. There is no income for this case, the energy availability is high, and its generation risk is very low because the system has been inherently designed with redundant procedures for emergencies. One of the most negative points of such systems is the emissions damaging the environment. High emissions of the offshore oil and gas platforms in the Persian Gulf should be known as a catastrophic environmental problem. The rate of the emissions is increasing because the fields are becoming old and their production rates are decreasing. As a reaction to the problem of the decrease in the production rate, oil companies have to apply field performance enhancing methods such as water or gas injection to keep their exporting rates. These methods are also power intensive and will add a surplus to the rate of power generation and the rate of the associated emissions.

4. New Grid: Wind Farm, National Grid, and Offshore Platform

In this scenario, the field owner company constructs an onshore/offshore wind farm consisting of a specified number of wind turbines. This farm which has at least a capacity enough to fulfill the accumulated yearly demand of the Soroush platform is connected to the national grid. The farm distance from the platform is not important. Generated power from the farm is sold to the national grid totally. Moreover, the platform buys its required amount of power from the national grid instead of burning natural gas in onboard gas turbines. Figure 3 shows a schematic of the first scenario of the current study.

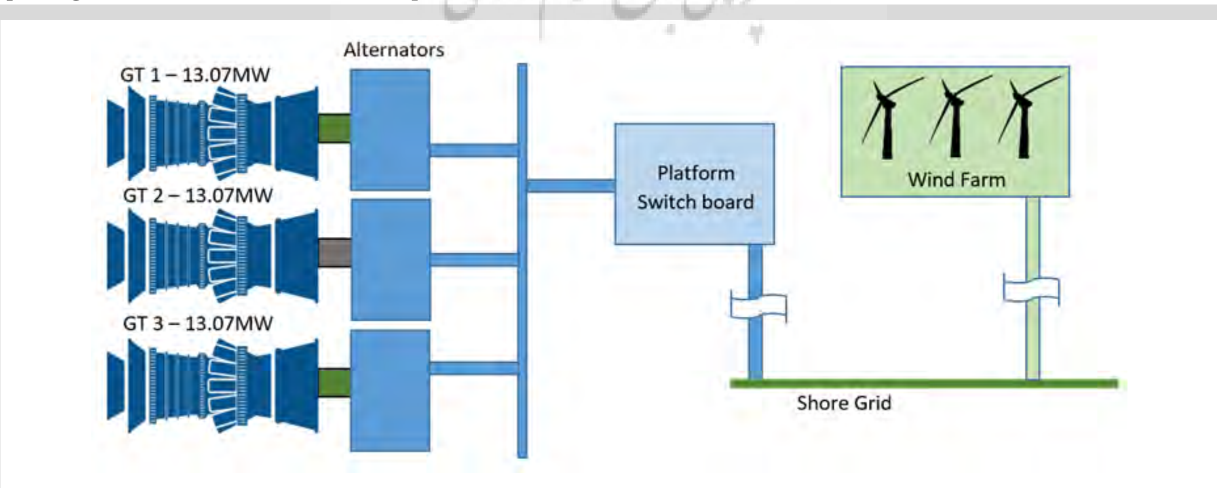

Figure 3. Purposed grid of the current study.

Cost terms related to the power generation system of the Soroush offshore complex in the first scenario are:

- Cost of power to be bought from the national grid;
- Cost 1 which equals the annual platform demand multiplied by the natural grid power price;
- Capital expenditures (CAPEX) and operational expenditure (OPEX) of the wind turbines;
- Natural gas being burnt in the gas turbines in the case of the grid power shortage (an assumption for contingency);

The CAPEX and OPEX of power cables from the platform to the shore are not considered because it is supposed that the platform already has such connections and these cables are not going to be added to the platform.

- Income terms related to the power generation system of the Soroush offshore complex in the first scenario are as follows:
- Income from selling the wind farm generated power to the national grid;
- Income 1 which equals the wind farm generated power multiplied by renewable energy selling price;
- Income from exporting more amount of natural gas; the amount which is not burning in gas turbines anymore;

The energy availability and generation appear to be stable because the power system of the platform has:

- Income 2 equaling the annual platform demand multiplied by the natural gas exporting price;
- The capability and ability to take the responsibility of the total demand in the case of any grid power problem or shortage.

This scenario produces very low emissions. To be measured, there is almost no emission being produced from the offshore complex because the power is generated somewhere else in a wind farm and the platform has no gas turbines on duty under normal working conditions.

5. Results

Knowing the average wind speed in each month makes it possible to estimate how much power is generated during a year. Here the only available recorded logs are the monthly average of the wind speed at a height of 10, 30, and 40 m in Bardekhun station, which is located near the offshore complex in Bushehr province. Figure 4 shows the average wind speed in Bardekhun station. Because the turbine hub is placed at a height of 90 m, the data on the wind speed have been transferred and converted from a height of 40 m to a height of 90 m using Eqs. (1) and (2).

It is obvious that each turbine experiences its least generation period in August, September, and October because the average wind speed hardly passes the considered the cut-in speed of the turbine as shown in Figure 4. Figure 5 displays the distribution of the wind speed average for each month during a year.

The wind turbines considered to be used in the assumed farm of the study are from Siemens 3.6 MW category turbines which have a hub height of about 90 m from its base. The cut-in and cut-off speed of this turbine is 3.8 and 25 m/s respectively. Further, its rated power is 3.6 MW which is achieved at a wind speed of 13 m/s. Figure 6 shows the mean generated power curve of the turbine.

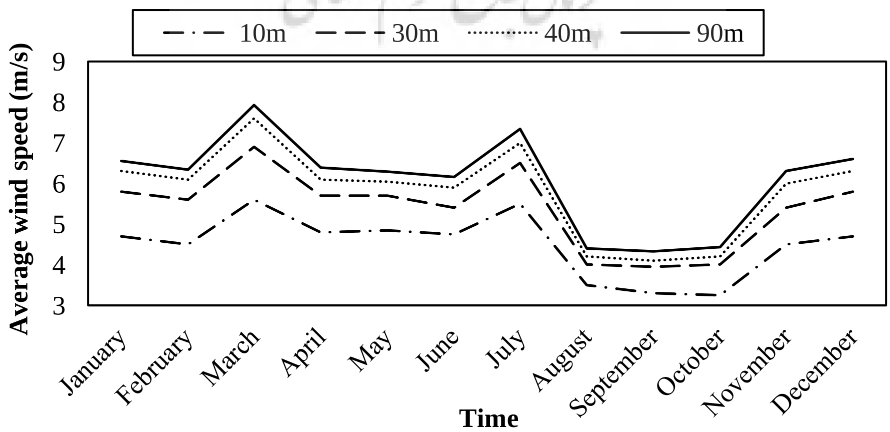

Figure 4. Average wind speed in Bardekhun station.

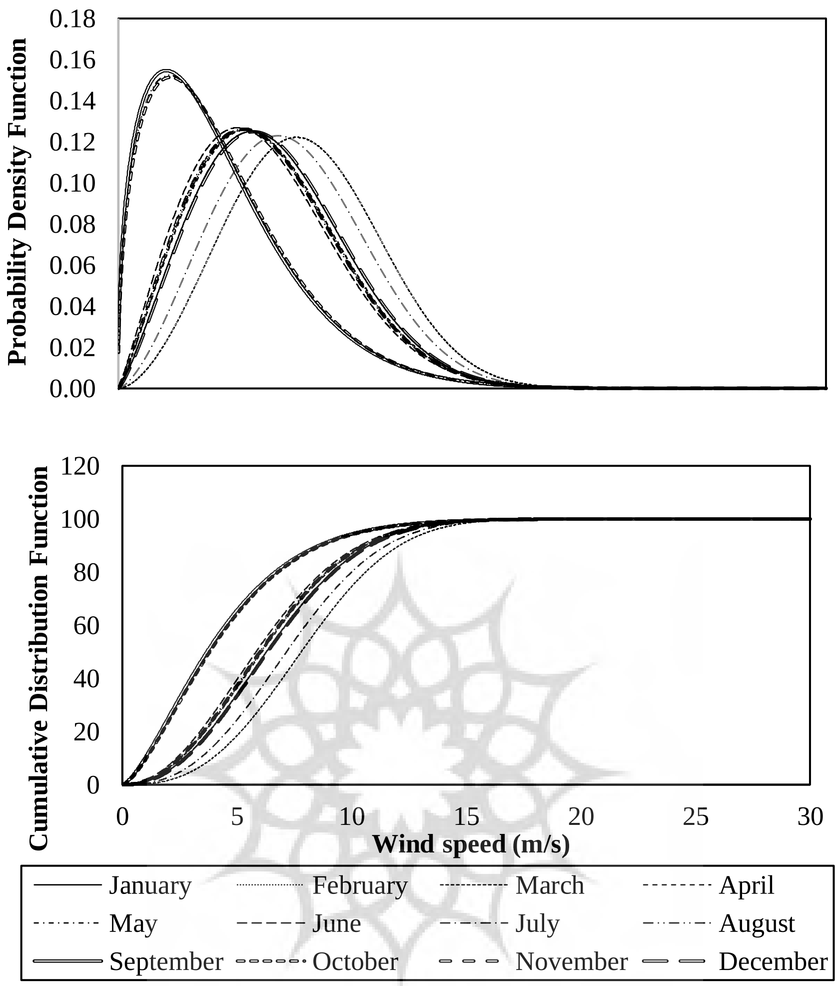

Figure 5. Monthly wind speed distributions in Bardekhun station.

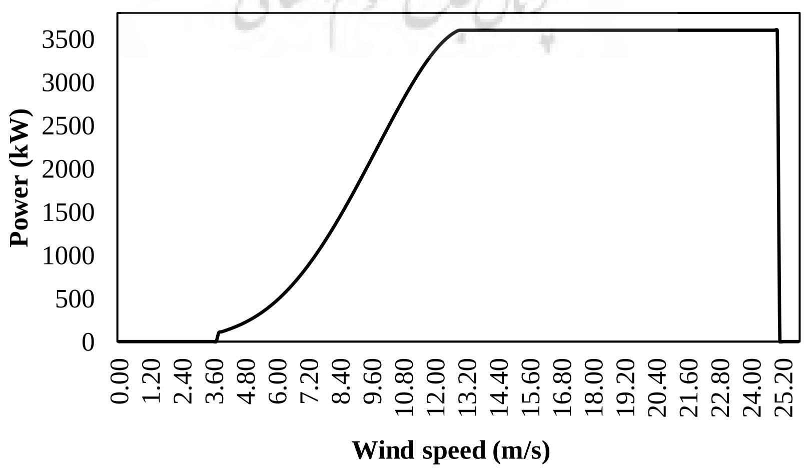

Figure 6. The average power curve of Siemens 3.6 MW wind turbine.

The adopted formula for the standard deviation of the motioned wind turbine is presented in Eq. (6). A normal distribution can be used at each velocity for the probability of the power performance of wind turbine (Amirinia et al., 2016).

$$\sigma_P = \begin{cases} \left] -\frac{0.35(V - V_R)}{V_R - V_I} + 0.1 \right] \mu_{P(V)} \Big/ \sqrt{6} & V_I \le V \le V_R \\ 0.1\mu_{P(V)} \Big/ \sqrt{6} & V_R \le V \end{cases} \tag{6}$$

The power demand of the platform in a day is also considered to be as shown in Figure 7. The yearly demand of the platform is generated by using this general daily pattern.

This offshore complex supplies its total power demand by burning natural gas in its onboard thermal power plant which consists of three gas turbines. Regarding the demand pattern in Figure 7 and the natural gas price, the total yearly fuel cost of the offshore complex is calculated as presented in Table 2.

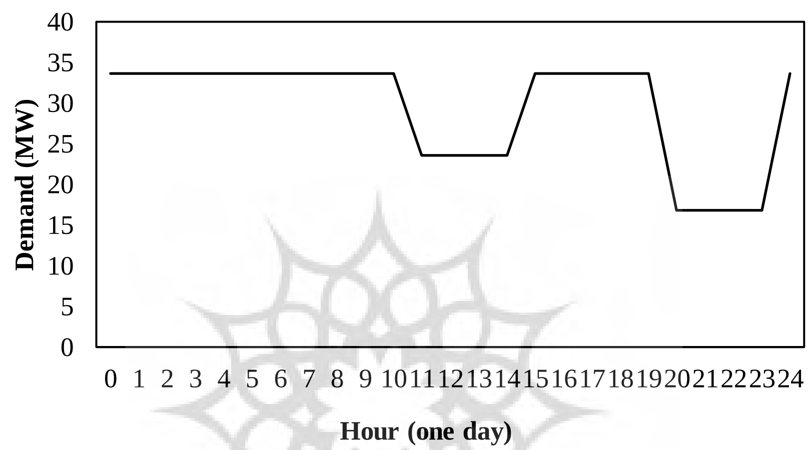

Figure 7. The daily power demand of the platform.

Table 2. The annual fuel cost of the offshore complex.

Natural Gas Price is considered to be 0.04 USD/kWh (EIA's International Energy Outlook, 2017)				
Rated Power (MW)	**Rated Power (%)**	**Cost (USD/Hour)**	**Time (Hour/Year)**	**Total Cost (Million USD/Year)**
33.63	100	1,345.48	5840	7.85
23.54	70	941.84	1460	1.37
16.81	50	672.74	1460	0.98
One Year Fuel Cost				10.21

To estimate the average required numbers of the Siemens 3.6 MW wind turbines to be installed in the farm, it is assumed that the yearly power generation of the farm has to fulfill the yearly power demand of the offshore complex. Therefore, using Eq. (5), which requires the wind speed probability and the turbine power generation at that speed, Figure 5, and Figure 6, the yearly power generation of a single Siemens 3.6 MW wind turbine is calculated. It is predicted that 34 turbines of the same capacity are required to satisfy the considered conditions as calculated in Table 3.

Figure 8 shows the probability of the monthly power shortage or power excess of the farm relative to the monthly demand of the platform. Considering the fact that the monthly shortage of power is being supplied by the onboard thermal power plant in the platform, monthly fuel cost savings and emission reductions are calculated.

The market price of the natural gas and the price of selling the renewable energy to the national grid is respectively 40 and 89.13 USD/MWh (Ministry of Energy, 2016). Table 4 lists the monthly average amount of the power excess and power shortage in economic terms and the related probabilities. It is considered that the power shortage is supplied by burning natural gas in gas turbines and the excess of the power supply is exported to the national grid.

Table 3. The average required numbers of the Siemens 3.6 MW wind turbines.

Rated Power (MW)	33.63	23.54	16.81
Time (Hour/Year)	5840	1460	1460
Yearly Demand (MWh)			255372.10
Farm Scale "Numbers of Siemens 3.6 MW wind turbines"			34

The power generation system of the offshore complex in its real present condition is considered as the base case, and the proposed combined system in this study is considered as the proposed scenario. The mentioned cases are compared to the annual costs of energy and relative emissions as listed in Table 5.

As per the report of National Renewable Energy Laboratory (NREL), the levelized cost of energy (LCOE) for the CAPEX and OPEX of the wind turbines are 45 and 15 USD/MWh respectively (Mone et al., 2015). The annual average revenue of the power system for the proposed scenario is calculated by applying the probabilities of the power excess and power shortage to their mean values for a year.

As is listed in Table 5, the hybrid power system requires a considerable investment cost in the first year, but this investment will return in less than two years because the annual cash flow for the years after the first year is large and positive. In addition, it makes it possible to increase the income of the gas export. The proposed scenario exports a portion of the gas burnt annually in order to generate power as considered in the base case. Thus, the proposed scenario has a lower rate of annual emissions relative to the base case.

The hybrid power system in the proposed scenario consists of a thermal and a renewable power plant. The combined power generation in this hybrid system has more reliability in comparison to the base case because the remained thermal plant capacity will be assumed as the contingency resource of the system.

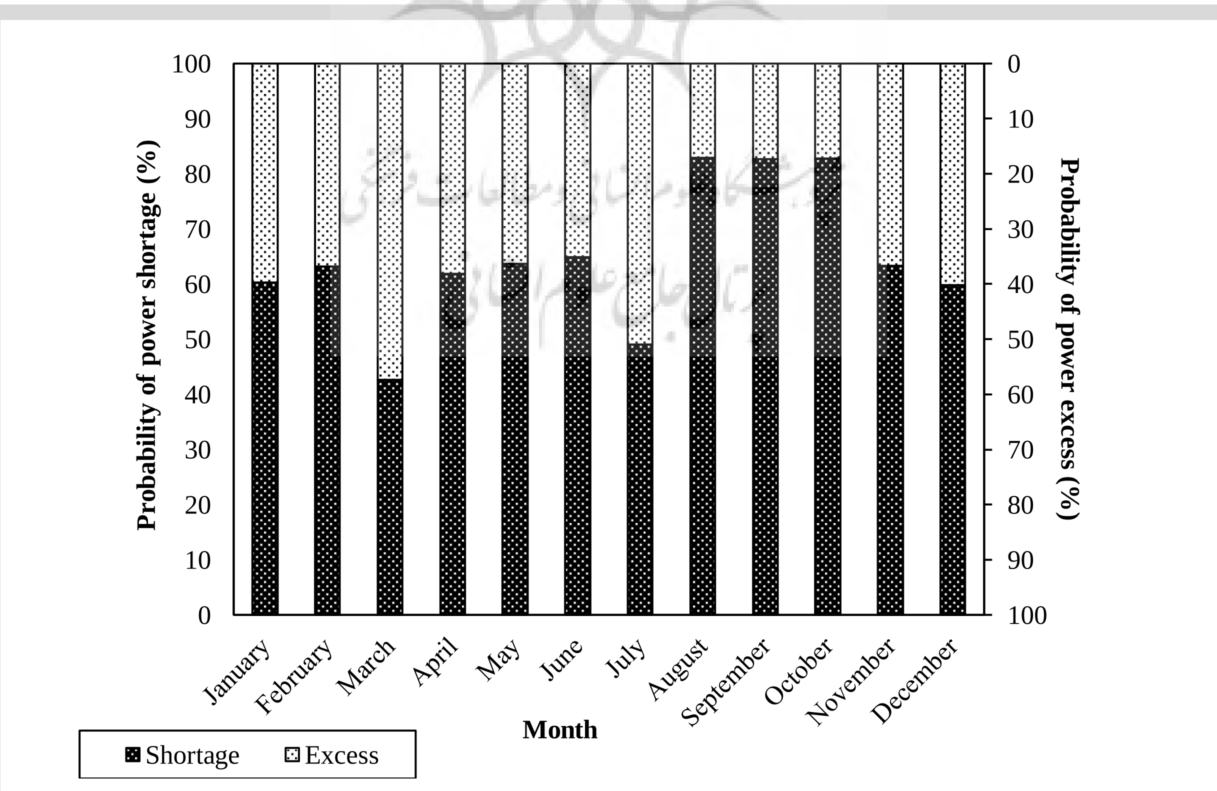

Figure 8. Probability of power shortage or power excess in each month.

Table 4. The probability of the monthly average power excess or power shortage and its consequence revenue.

Month	Income Average ($)		Probability of excess (%)
	Excess	Shortage	
January	2,705,755	–605,382	39.67
February	2,571,302	–583,342	36.81
March	2,793,894	–572,950	57.30
April	2,752,962	–579,502	38.10
May	2,742,000	–589,337	36.28
June	2,715,509	–593,460	35.07
July	2,753,110	–589,266	50.89
August	2,745,555	–613,999	17.08
September	2,734,969	–629,098	17.32
October	2,727,170	–642,226	17.20
November	2,712,967	–638,106	36.72
December	2,715,805	–635,180	40.20

Table 5. Comparison of the platform power systems.

	Offshore complex	
	Base case	Proposed scenario
Annual average power demand (MWh)	255,372.104	255,372.104
Power generation unit	Thermal Power Plant	Combined Power Plant (Thermal and Renewable)
System components	Gas turbines 3×13.07 MW	Gas turbines (3 × 13.07 MW plus 4 × 3.6 MW wind turbines)
CAPEX (Mone et al., 2015) (Additional) (Million $)	-	–12.51
Annual average OPEX (Mone et al., 2015) (Additional) (Million $)	-	–3.83
Annual average power revenue (Million $)	–10.21	+6.78
Annual average natural gas exporting (Million $)	-	+2.94
Emissions (Relative)	1	0.71

6. Economic Evaluation Results

The proposed scenario of this study is then compared in terms of the considered economical aspects of interest. Total manufacturing, transferring, and installation costs of the wind farm and batteries are counted in the investment stage for the scenario. The total cost of the wind farm for the scenario is calculated applying one of the assumptions of the study. The assumption indicates that the satisfactory minimum power generation of the wind farm should be equal to the total yearly demand of the complex. Table 6 presents the results of the economic evaluation of the proposed scenario.

Table 6. Economic evaluation results of the proposed scenario.

		All prices are in Million USD; Pay back ratio (PBR) is in year.	
		Base case	**Proposed scenario**
Investment (Average)		0	–12.51
First year (Average)		–10.21	33.93
25-year life span	**NPV (10% WACC)**	–93.57	268.62
	IRR (%)	-	271%
Pay back ratio		-	0.37

7. Conclusions

Considering the technical and environmental problems resulted from the off-design running conditions of the processes in a platform and the absence of any strategies to stop or decrease the greenhouse gas emissions of these platforms, modern methods of energy generation from available renewable potentials near offshore platforms are suggested. Recent developments in renewable energy technologies have extensively decreased the price for each unit of the generated power and reduced the greenhouse gas emissions.

The integration of renewable energy converters with offshore oil and gas platforms will solve both problems with the machinery and the environment to an acceptable extent. The integrated platform will be able to sell its extra generated power to its neighbor platforms or to the shore via cables. In this study, the economics and emissions of the offshore complex are examined considering two different power generation method cases. The base case defines the present conditions in which the total power demand of the complex is supplied by burning the onboard extracted natural gas in the platform, and the proposed scenario considers an imaginary wind farm consisting of 34 Siemens 3.6 MW wind turbines which are located near Bardekhun station in Bushehr province, are connected to the complex power network, and shares their power generated by renewable sources with the platform. The proposed scenario has a considerably less amount of annual emissions and results in even power incomes instead of costs. Decreasing the onboard combustion of natural gas in thermal plants causes a decrease in the annual emissions and the associated financial penalties. Increasing the export rate of natural gas will be another result as it is not burnt onboard at previous rates anymore. This income is considered in the case of the platforms having gas export facilities. Considering the proposed scenario after the lifetime of the offshore complex, the wells are plugged, platforms are abandoned, but the wind farm continues its power generation, making absolute income for the owner company. The calculations performed for renewable power generation in this study are based on horizontal axis wind turbine (HAWT) technology and their available experimental data, which are generally being used worldwide. Considering vertical axis wind turbine (VAWT) technologies in future years, which are believed to have higher efficiency and power output capacity in addition to lower operational and maintenance costs, increases the difference in the total cost of both scenarios and makes the proposed scenario more and more economically attractive.

Nomenclature

C	Reference point height
Hs	Surface roughness
K	Wave significant height
LP	Wave length
Pw (U)	Wave period
T	Weibull shape factor
U(z)	Weibull scale factor
U_{ref}	Wind speed average
Z_0	Standard deviation of wind speed
Z_{ref}	Mean annual power generated by a wind turbine
σ_U	Turbine power at a wind speed of U
$\overline{U}$	Wind speed at a height of Z
$\overline{P_w}$	Wind speed at the reference height

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