Sustainable offshore oil and gas fields development

Techno-economic feasibility analysis of wind–hydrogen–natural gas nexus

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Research paper

Sustainable offshore oil and gas fields development: Techno-economic feasibility analysis of wind–hydrogen–natural gas nexus

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ABSTRACT

Offshore oil and gas field development consumes quantities of electricity, which is usually provided by gas turbines. In order to alleviate the emission reduction pressure and the increasing pressure of energy saving, governments of the world have been promoting the reform of oil and gas fields for years. Nowadays, environmentally friendly alternatives to provide electricity are hotspots, such as the integration of traditional energy and renewable energy. However, the determination of system with great environmental and economic benefits is still controversial. This paper proposed a wind–hydrogen–natural gas nexus (WHNGN) system for sustainable offshore oil and gas fields development. Combining the optimization model with the techno-economic evaluation model, a comprehensive evaluation framework is established for techno-economic feasibility analysis. In addition to WHNGN system, another two systems are designed for comparison, including the traditional energy supply (TES) system and wind–natural gas nexus (WNGN) system. An offshore production platforms in Bohai Bay in China is taken as a case, and the results indicate that: (i) WNGN and WHNGN systems have significant economic benefits, total investment is decreased by 5,190 and 5,020 million $ respectively, and the WHNGN system increases 4,174 million $ profit; (ii) WNGN and WHNGN systems have significant environmental benefits, annual carbon emission is decreased by 15 and 40.2 million kg respectively; (iii) the system can be ranked by economic benefits as follows: WHNGN > WNGN > TES; and (iV) the WHNGN system is more advantageous in areas with high hydrogen and natural gas sales prices, such as China, Kazakhstan, Turkey, India, Malaysia and Indonesia.

1. Introduction

It is estimated that the global energy demand will increase by 28% from 2015 to 2040 (International Energy Agency (IEA), 2017). Today, it relies mainly on fossil fuels (oil, gas and coal) (Musa et al., 2018). Offshore oil and gas production is crucial to meet the world's rapidly growing energy demand. Since 2000, offshore oil and gas facilities have accounted for 30% and 27% of the world's oil and gas production respectively (Crivellari et al., 2021). Offshore oil and gas field development consumes quantities of electricity, varying from 10 MW to several hundreds of MW (Seeking et al., 2021). Traditionally, the electricity is provided by gas turbines, which is installed on a platform, and operated by combustion of natural gas (Nguyen et al., 2016). In fact, it was considered a waste and no environmentally friendly. So, under the global trend of low-carbon transformation, how to establish and develop sustainable offshore oil and gas fields has become a huge challenge (Qiu et al., 2021). It is urgent to promote oil and gas fields reform through the integration of traditional energy and renewable energy (Xy et al., 2019). As the main force of renewable energy, wind energy has been exploited on a large scale in recent years (International Energy Agency , IEA). In 2019, 146 offshore wind farms were built and put into operation in the world, with a total installed capacity of 5.2 GW, mainly distributed in China, the United Kingdom, Germany, Denmark, and Belgium, with a cumulative installed capacity of 27.2 GW, a year-on-year increase of 23.4% (Wu et al., 2020). Despite the rapid investment in wind energy, the intermittency characteristic of wind energy is inevitable and will cause wind electricity curtailment problems and at present, wind–hydrogen technology is a promising solution to alleviate this problem (Wang et al., 2019). The use of wind energy and other renewable energy to produce hydrogen, achieve

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multi-channel efficient utilization of renewable energy is one of the important directions for the integration of traditional energy and renewable energy in the future (Oliveira-Pinto et al., 2019). However, high transportation costs hinder the further development of hydrogen applications. Hydrogen–natural gas blending technology is considered a promising solution to alleviate this problem (Andrzej et al., 2018).

Facing the increasingly prominent energy and environmental situation, it is important to integrate offshore oil and gas fields with the development of electricity supply systems with low investment, convenient maintenance and management (Zhang et al., 2017a). However, the current development situation is still far away from the goal. For offshore oil and gas fields system, the structure of energy consumption and supply is relatively complicated (Zhang et al., 2017b). Many scholars have verified the techno-economic feasibility of wind-to-power, wind-to-hydrogen, hydrogen–natural gas blending transportation technology (Makitie et al., 2019; Valdes et al., 2013). However, few of them have combined these three technologies and applied it to the development of offshore oil and gas fields. The WHNGN system in offshore oil and gas fields proposed in this paper is a multi-energy complementary system. In offshore oil and gas fields, traditional energy and renewable energy is used to generate electricity to meet the electricity demand of oil and gas production, excess electricity is used to produce hydrogen, and the produced hydrogen and natural gas are blending transported to the onshore gas gate station. The purpose of this paper is to discuss the coupling effects of some systems, analyze the economic and environmental benefits of these systems in the real scene, and help determine whether the WHNGN system can be applied to a certain area under specific conditions, so as to coordinate the development of offshore wind power and offshore oil and gas field development.

The rest of the paper proceeds as follows. Literature review are provided in Section 2. Section 3 describes the study problem and system in detail. The energy supply system design model and economic and environmental analysis methods are given in Section 4. Section 5 presents the case and Section 6 analyzes and discusses the results. Section 7 is discussion. Finally, conclusions are drawn in Section 8.

2. Literature review

At present, there are more and more researches on the energy system optimization of offshore oil and gas fields. Most scholars have put up new ways to save energy and reduce consumption for offshore oil and gas fields, such as establishing a cogeneration system through waste heat recovery, optimizing equipment parameters to obtain the best operation scheme, and combining renewable energy with traditional power generation system (Zheng et al., 2019). Silva et al. (2020) studied advanced cogeneration and carbon capture systems in the context of offshore oil platform power supply, and evidenced how advanced gas turbine concepts are promising technologies for maintaining or even increasing efficiency, while facilitating the capture rate of CO_2 produced, either for geological storage or enhanced oil recovery. Voldsund et al. (2014) based on the exergy analysis method, analyzed and compared the oil and gas processing plants of four North Sea offshore platforms. The comparison of the sources to exergy destruction and exergy losses illustrated the large exergy destruction associated with the gas treatment, gas recompression and production manifold systems, and these systems were improved to achieve the purpose of energy saving and consumption reduction. Gallo et al. (2017) focused on diagnosing the compression systems used in the proposed FPSO and concluded that fuel consumption and greenhouse gas emissions of offshore oil and gas platforms could be reduced by reducing equipment replacement and improving the efficiency of the pump and compressor systems. Oliveira-Pinto et al. (2020) investigated the feasibility of integration wave and solar energy systems for power supplying offshore oil and gas platforms. The results show that the integration of both renewable resources increases electricity production, reduces the intra-annual variability of energy production and intermittency issues, increases capacity factors up to 24% and consequently avoids overdesign. The obtained levelized cost of energy is in the range 131–263 €/MWh and the reduction in emissions was estimated at circa 281,915 ton/year.

Moreover, it is possible to use offshore wind turbines to power supply oil and gas field. Korpås et al. (2012) studied the possibility of operating a 4 × 5 MW offshore wind farm in parallel with gas turbines. Hu et al. (2008) proposed a stability assessment method for wind power systems on isolated offshore oil platforms. The simulation results show that wind turbine generator systems can be including in conventional isolated power systems, such as offshore oil platform power systems, which can reduce operating costs by reducing fuel consumption and prove the impact of connection of wind power on the voltage and frequency stability can be accepted lately. At present, there are already offshore oil and gas fields that receive electricity from offshore wind turbines (for example, the Beatrice wind farm, which consists of 2 × 10 MW wind turbines connected to the Beatrice AP platform via submarine cables. It was put into use in 2007 and deployed at a depth of 45 m (Legorburu et al., 2018)).

In addition, a more profitable alternative has been used in this paper, which is wind-to-hydrogen technology. Some scholars have studied the feasibility of hydrogen production from renewable energy sources such as wind and solar energy. For example, Mehmet and Binish (2015) proposed an integrated hydrogen production system combining both nuclear and solar energy sources, this system includes storage of hydrogen and its conversion to electricity by fuel cells when needed. Al-Sharafi et al. (2017) studied the feasibility of power generation and hydrogen production via solar and wind energy resources at different locations in the Kingdom of Saudi Arabia and analyzed the effects of changing solar radiation and wind speed on the power generation. The results show that integration of 2 kW PV array, 3 wind turbines, 2 kW converter and 7 batteries storage bank is the best configuration that leads to the minimum levelized cost of energy (COE) of 0.609 $/kWh. McDonagh et al. (2020) have established an economic evaluation model for the hydrogen production system of offshore wind farms, and analyzed the economic efficiency of three scenarios: all electricity is sold to the grid; all electricity is converted to hydrogen and sold; and a hybrid system where power is converted to hydrogen when curtailment occurs and/or when the system marginal cost is low. All above studies prove the feasibility of wind-to-hydrogen technology.

Using the hydrogen–natural gas blending transportation technology can make full use of the existing pipeline facilities and reduce the transportation cost of hydrogen (the natural gas pipeline network can blend with no more than 10% hydrogen) (Witkowski et al., 2018; Dashtebayaz et al., 2019). Vries et al. (2017) assessed the changes in safety and fitness for purpose of domestic natural gas appliances when supplied with natural gas/hydrogen mixtures and the results demonstrate that the maximum amount of hydrogen in natural gas depends on the composition of the natural gas. Korsakas et al. (2017) experimentally investigated the effect of hydrogen addition on the efficiency and ecological parameters of the heavy-duty vehicles for from 5 vol% up to 20 vol% in the natural gas fuel. Deymi-Dashtebayaz et al. (2018) blended of produced hydrogen from renewable energy resources into the natural gas grid and found that when the mixed hydrogen concentration is between 1% and 10%, there is no need to change the equipment. Schouten et al. (2004) calculated the influence of hydrogen on the thermodynamics upon injection, on the Joule–Thomson effect at the pressure reduction stations, on the energy density, on the Wobbe index, and on the pressure drop in the pipelines. Timmerberg and Kaltschmitt (2019) investigated the costs and potentials for hydrogen produced on the basis of electricity from wind and solar energy in North Africa and the subsequent transport as a blend with natural gas in existing pipelines. All above studies prove the feasibility of hydrogen–natural gas blending transportation technology.

It can be seen that many researchers have discussed the techno-economic feasibility of wind-to-power, wind-to-hydrogen, hydrogen–natural gas blending transportation technology, but few of them combine the three technology into the offshore oil and gas fields. At present, there is a lack of guidance in this aspect in practical research.

Based on the above analysis, this paper aims to design a system, which combines wind-to-power, wind-to-hydrogen, hydrogen–natural gas blending transportation technology and apply it to offshore oil and gas fields. And establish energy supply system design and economic and environment evaluation model to solve the most economic energy equipment configuration. According to the structure of energy system and the types of available energy carriers, this paper establishes three energy system schemes: traditional energy supply (TES) system, wind–natural gas nexus (WNGN) system, wind–hydrogen–natural gas nexus (WHNGN) system. Among them, the emphasis is on the comparative analysis of the economic performance, equipment configuration and environmental protection effect of WHNGN system. In addition, the sensitivity of wind speed and gas selling price was analyzed. Finally, this paper analyzes the application of WHNGN system in different countries to provide strategic support for designers.

This research aims to make contributions from the following aspects.

(1) The WHNGN system is proposed for sustainable offshore oil and gas fields development, involving electricity generation system, oil and gas production system, hydrogen generation system and blending transportation system, which fills the blank of literature.

(2) An integrated framework is developed for evaluating the techno-economic feasibility of the WHNGN system.

(3) Through a real-world case of offshore oil gas field simulation calculation, the techno-economic feasibility of WHNGN system is determined. And the sales revenue and investment of three systems are calculated in detail.

(4) By the generalization analysis of in eight countries, it concluded that the WHNGN system is more beneficial in China, Kazakhstan, Turkey, India, Malaysia and Indonesia.

3. Problem description

The WHNGN system proposed in this paper is a typical energy integration system, which aims to optimize and transform offshore oil and gas fields by using renewable energy. It mainly includes four components: (A) Oil and gas production system, (B) Electricity generation system, (C) Hydrogen generation system and (D) Blending transportation system.

Oil and gas production system is the main electricity consumption system of offshore oil and gas fields, it has oil and gas production, oil and gas water treatment, and oil and gas storage function. It mainly includes production module, oil and gas processing module, storage module, power supply module and life module. The gas production can be used as fuel, combustion, or export sales.

Electricity generation system is an electricity supply system of offshore oil and gas production system. Electricity is generated by wind turbines and gas turbines. The fuel of gas turbine is natural gas from the production system. In addition, to make up for the random characteristics of wind electricity generation, batteries are added to provide electricity peak load regulation services.

The hydrogen generation system uses the excess electricity in electricity generation system to produce hydrogen through electrolysis, which improves the energy efficiency. The electricity is taken according to the demand, and the hydrogen is produced by electrolysis after AC/DC conversion. Due to the instability of wind energy, the rate of hydrogen generation is unstable. Therefore, the hydrogen is stored in the hydrogen storage tank first, and then mixed into the natural gas pipeline with a volume ratio of no more than 10% according to the hydrogen demand for stable transmission.

For the blending transportation system, hydrogen produced by electrolysis is mixed with natural gas produced by the offshore platform in a certain proportion and transported to the onshore gas gate station for sale as fuel gas. After being processed by testing, purification, measurement and pressure adjustment, distributed to the need of the place.

In order to analyze the influence of each subsystem on the techno-economic feasibility of the whole system, in addition to WHNGN system, another two systems are designed for comparison, three systems scheme shown in Fig. 1. The system settings are presented as below.

(1) TES system (Nguyen et al., 2016). In this system, electricity is supplied by gas turbines and the fuel of gas turbines is natural gas from the production system. The natural gas fired electricity and residual natural gas combustion result in a large amount of CO_2 emissions. TES system is set as the baseline for comparison.

(2) WNGN system (Zhang et al., 2021b). In this system, the offshore oil and gas fields are powered by wind turbines and gas turbine engines at the same time. At this time, because of less natural gas fired electricity, the amount of residual natural gas will increases. There will still be a large amount of CO_2 emissions.

(3) WHNGN system. The wind turbines and gas turbine engines supply electricity to the offshore oil and gas fields at the same time, and use the excess electricity to produce hydrogen. Finally, the hydrogen produced is mixed with natural gas to the onshore gas gate station, which is also the main form of this paper study. At this time, no natural gas combustion so there is only a few amount of CO_2 emissions produced in natural gas fired electricity.

4. Methodology

Based on the above description, the optimization model and economic and environment evaluation model for the above three systems is given, a comprehensive evaluation framework is established for techno-economic feasibility analysis.

4.1. Framework of this work

The roadmap of the proposed approach is given in Fig. 2. Firstly, taking the minimum total net present cost (NPC) as the objective function, considering the energy balance and design constraints, an energy supply system design MILP model is established based on HOMER to estimate NPC of offshore oil and gas fields. Secondly, the net present value (NPV) including transportation cost and gas sales revenue and is calculated by an economic evaluation model, and the carbon emissions is calculated by an environment evaluation model. Thirdly, considering the above models, the techno-economic feasibility of the three systems is compared, and get the optimal operating strategy. Ultimately, the generalization analysis of this research has been

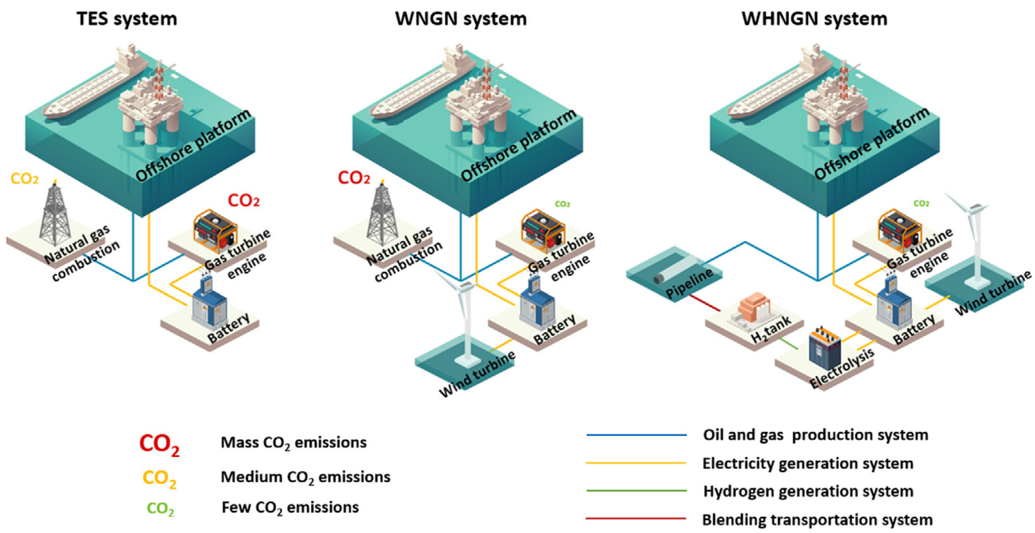

Fig. 1. Description of three systems.

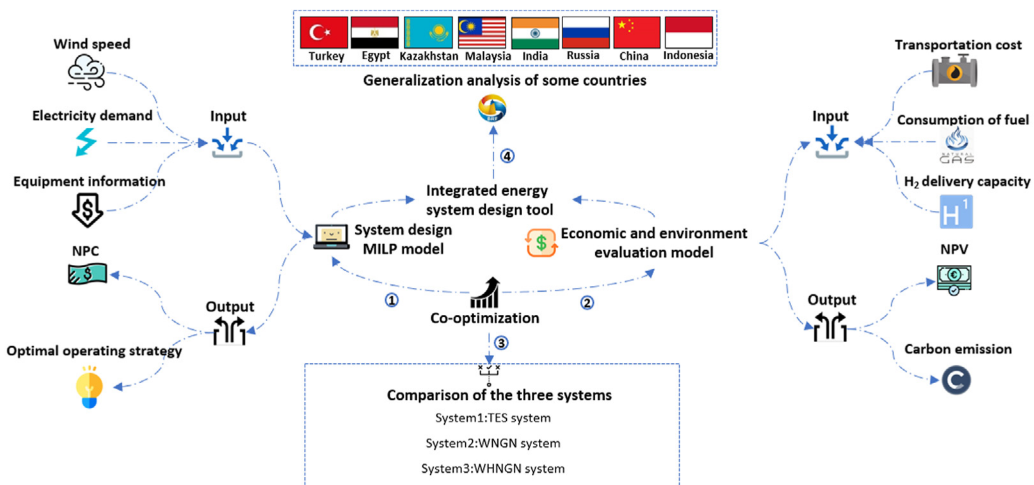

Fig. 2. Framework of the proposed approach.

done in eight countries include China, Kazakhstan, Turkey, India, Malaysia, Russia, Egypt and Indonesia.

We can see that the input parameters of energy supply system design MILP model are local wind speed, daily and hourly electricity demand, technical and cost information on equipment, output parameters are optimal operating strategy and total net present cost. The input parameters of the economic and environment evaluation model are correlation coefficient of transportation cost, consumption of fuel and hydrogen transportation capacity, the output is the maximum NPV and carbon emission.

4.2. Energy supply system design MILP model

In this section, the objective and constraints of energy supply system design MILP model to achieve reliable-economical trade-off are given.

4.2.1. Economic objective

In this section, the research goal is to determine the minimum cost to meet the electricity demand of users, so we taking the minimum expenditure in the whole time of the energy system as the objective function, which is expressed as NPC shown in the following Eq. (1) (Qiu et al., 2020), where including initial capital cost C_{Ini}, operating cost C_{Ope}, fuel cost C_{Fue} and salvage Cost C_{Sal}, it can be described as follows:

$$\text{MinNPC} = C_{Ini} + C_{Ope} + C_{Fue} - C_{Sal} \tag{1}$$

The initial capital cost C_{Ini} is the total installed cost of the system at the beginning of the project. The operating cost C_{Ope} is the value of all costs other than initial capital costs, it includes the cost of equipment operation and maintenance. The formula is as follows.

$$C_{Ini} + C_{Ope} = \sum_{f} (B_f W_f CF_f + T_f CL_f) \tag{2}$$

Where, B_f is a binary variable, when the system selects device f, $B_f = 1$, otherwise $B_f = 0$. CF_f is the linear capacity-dependent cost of equipment of device f. W_f is a continuous variable, which represents the rated capacity of the system equipment f. T_f is the operation time of the system device f. CL_f is the cost of device f which changes linearly with operation time.

The fuel cost C_{Fue} is the cost of fueling of gas turbine, we calculate this value by multiplying the fuel price P_{Fue} by the amount of fuel L_{Fue} used by the gas turbine. The salvage value C_{Sal} is the value remaining in a component of the system at the end of the project lifetime. The formula is as follows.

$$C_{Fue} = P_{Fue} L_{Fue} \tag{3}$$

$$C_{Sal} = \sum_{f} \left\{ C_{repf} \times \frac{R_{compf} - \left[R_{projf} - R_{compf} \times INT\left(\frac{R_{projf}}{R_{compf}} \right) \right]}{R_{compf}} \right\} \tag{4}$$

Where, C_{repf} is replacement cost of device *f*. R_{compf} is component lifetime of device *f*. R_{projf} is project lifetime of device *f*.

4.2.2. Energy balance constraints

In this section, considering the energy balance constraints, it is divided into electricity energy and hydrogen balance.

Firstly, the electricity balance constraint is considered to promote the coordination of power supply and demand. The electricity balance calculation is shown in Eq. (5) (Rui et al., 2018). It mainly means that electricity demand is equal to the electricity generated by the generator and wind turbine, the battery discharge, minus the battery charge, the electrolyzer input and excess electricity. $P_{t,f}^{COU}$ is energy output of device *f* in time window *t*. $P_{t,BT}^{DIS}$ is discharging energy of the battery at time window *t*. $P_{t,BT}^{CH}$ is charging energy of the battery at time window *t*. $P_{t,ET}^{CIN}$ is energy input of electrolyzer in time window *t*. $P_{t,EC}^{EXC}$ is excess electricity of system at time window *t*. $P_{t,EC}^{DEM}$ is demand for electric energy of the system at time window *t*.

$$P_{t,WT}^{COU} + P_{t,GT}^{COU} + P_{t,BT}^{DIS} - P_{t,BT}^{CH} - P_{t,ET}^{CIN} - P_{t,EC}^{EXC} = P_{t,EC}^{DEM} \tag{5}$$

The output of device *f* calculation is shown in Eqs. (6)–(7). $P_{t,wt}$ is electricity generated by a wind turbine sweeping over a unit area. A_{wt} is Total area swept by the wind turbine. $\eta_{GT,elec}$ is power production efficiency of gas turbines. $Q_{t,GT}$ is output energy of gas turbine at time t.

$$P_{t,WT}^{COU} = P_{t,wt} \times A_{wt} \tag{6}$$

$$P_{t,GT}^{COU} = \eta_{GT,elec} \times Q_{t,GT} \tag{7}$$

The second is hydrogen balance, which is similar to the electricity energy balance. The hydrogen balance calculation is shown in Eq. (8). The hydrogen demand is equal to the hydrogen generated by the electrolyzer, the tank discharge, minus the tank charge and excess hydrogen. $P_{t,ET}^{COU}$ is energy output of electrolyzer in time window *t*. $P_{t,HT}^{SOU}$ is energy discharged from hydrogen tank in time window *t*. $P_{t,HT}^{CH}$ is charging energy of hydrogen tank at time window *t*.$P_{t,HG}^{EXC}$ is excess hydrogen of system at time window *t*. $P_{t,EC}^{DEM}$ is demand for hydrogen energy of the system at time window *t*.

$$P_{t,ET}^{COU} + P_{t,HT}^{SOU} - P_{t,HT}^{CH} - P_{t,HG}^{EXC} = P_{t,HG}^{DEM} \tag{8}$$

4.2.3. Technical constraints

In order to prevent excessive installation capacity and avoid unnecessary output, the device capacity cannot exceed the set maximum value. At the same time, to ensure that the formula is non-negative and produce some wrong conclusions, the device capacity should also be greater than the minimum value.

Equipment capacity constraints. The rated capacity of the device must not exceed the maximum capacity. Max and Min are maximum and minimum capacity is allowed of device. It is shown in Eq. (9) (Zhang et al., 2021b).

$$(B_f - 1)\text{Min} \le W_f \le B_f \text{Max} \tag{9}$$

Equipment operation constraints. During the operation of each functional device, the energy input device must not exceed the rated capacity. $P_{t,f}$ is input energy of device *f* at time *t* window. W_f is the rated capacity of the system device *f*.

$$P_{t,f} \le W_f \tag{10}$$

4.3. Economic and environment evaluation model

In this section, economic and environment evaluation model for the above described wind–hydrogen–natural gas nexus system is given.

4.3.1. Economic and environment objective

In this section, the research goal is to determine the maximum profit of system, so the NPV is taken as the main evaluation standard of economic analysis of the system, which refers to the difference between income and expenditure over the project lifetime, as shown in Eq. (11). CR_t and CS_t are the system revenue and system cost in year *t* respectively. T_L is the project lifetime. *r* is the annual real discount rate.

$$NPV = \sum_{t=0}^{T_L} (CR_t - CS_t)(1+r)^t \tag{11}$$

Carbon emission (*CE*) is the standard of system environmental analysis. The calculation of carbon emission is shown in the following Eq. (12) (Zhang et al., 2021a), which is obtained by multiplying the annual consumption of fossil fuel and its corresponding carbon emission coefficient. Where Q_t^{Fuel} is the consumption of fossil fuel in year *t*; *CEF* is the carbon emission factor.

$$CE = \sum_{t=0}^{T} Q_t^{Fuel} \times CEF \tag{12}$$

Levelized energy cost of energy (COE) is the average cost per kWh of useful electrical energy produced by the system. It is divides the annualized cost of producing electricity by the total electric load served E_{served}, using the following Eq. (13). Total annualized cost $C_{ann,tot}$ is the annualized value of the total net present cost, calculates the total annualized cost using the following Eq. (14). The capital recovery factor (CRF) is a ratio used to calculate the present value of an annuity (a series of equal annual cash flows). The equation for the capital recovery factor is Eq. (15):

$$COE = \frac{C_{ann,tot}}{E_{served}} \tag{13}$$

$$C_{ann,tot} = \text{CRF}\left(i, R_{proj}\right) \times C_{\text{NPC},tot} \tag{14}$$

$$\text{CRF}\left(i, R_{proj}\right) = \frac{i(1+i)^{R_{proj}}}{i(1+i)^{R_{proj}} - 1} \tag{15}$$

4.3.2. Sales revenue and facility investment and operation cost

It can be seen from the following formula that the annual system revenue includes the sales revenue of natural gas and hydrogen, which depends on the transportation quantity of natural gas and hydrogen and the price of gas sales. Q_t^{NG}, $Q_t^{H_2}$ are the sales quantity of natural gas and hydrogen in t year respectively. P_t^{NG}, $P_t^{H_2}$ are the unit sales prices of natural gas and hydrogen in *t* year respectively. C_{Trans} is the cost of transportation system, which is given by Eq. (18). C_{pipe} represents the capital costs of pipeline, [$]; Fix_d^{pipe} represents the investment cost of pipeline with diameter *d*, [$]

$$CR_t = P_t^{H_2} Q_t^{H_2} + P_t^{NG} Q_t^{NG} \tag{16}$$

$$CS_t = \text{NPC} + C_{trans} \tag{17}$$

$$C_{trans} = C_{pipe} + OC_t^{pipe} \tag{18}$$

To calculation the cost of natural gas and hydrogen transportation technology, the capital cost, operation cost and maintenance cost of pipeline are included. In this study, the economic analysis model is used to estimate the cost of transportation via pipelines which is given by Eqs. (19)–(20). It should be noted that the

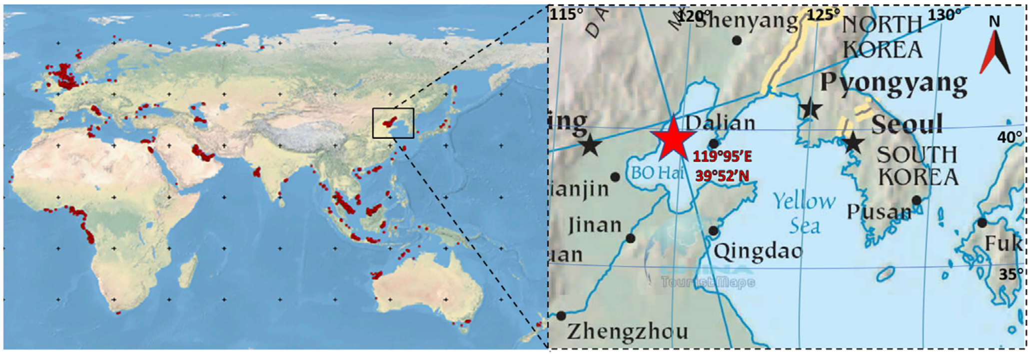

Fig. 3. The location of oil and gas fields, based on IHS database and this paper, 2019, (Anon., 0000a).

Table 1
Parameters used in the cost model of pipeline.

Diameter (in)	4.3
Fixed cost ($/km)	353,010
Unit cost ($/kg day)	0.056

operation and maintenance cost vary with mass of gas (Schell et al., 2017; Liu et al., 2019). The parameters are listed in Table 1.

$$C_{pipe} = Fix_d^{pipe} \times L \tag{19}$$

$$OC_t^{pipe} = U_d^{pipe} \times Mass_t^{pipe} \times 365 \tag{20}$$

Where, L is the construction length of the pipeline, [km]; OC_t^{pipe} is the operation and maintenance cost during year t, [$]; UC_d^{pipe} is the unit operation and maintenance cost of pipeline with diameter d, [$/kg day]; $Mass_t^{pipe}$ is the mass of natural gas and hydrogen transported through pipeline during year t, [kg].

5. Case study

In this section, a practical example from an offshore oil and gas field sited in Bohai Bay, China is given to demonstrate the feasibility of the proposed system.

5.1. Case object

In order to analyze the techno-economic feasibility of WHNGN system in offshore oil and gas fields, a site in Bohai Bay is selected for research and analysis. Fig. 3 depicts the global distribution of oil and gas fields based on IHS database, in which the Bohai Bay area is densely distributed. The selected location does not represent the actual location. Our goal is to find an area where these facilities can be installed. The longitude and latitude of the selected site in this section are 119°95′E and 39°52′N respectively. We assume that the oil and gas platform is 253.6 meters long and 32 meters wide, can accommodate 50 employees and the lifetime is 25 years. On this platform, the fluid from the wellhead is first separated by oil, gas and water through the three-phase separator. The separated crude oil enters the sedimentation tank through the electric dehydrator, and the associated gas is used as fuel gas after passing through the scrubber, residual natural gas is exported and sold together with the hydrogen produced by electrolysis through the pipeline.

5.2. Input data

In this section, the input data and data sources of the case are given, including wind speed, energy demand, technical and cost information on equipment.

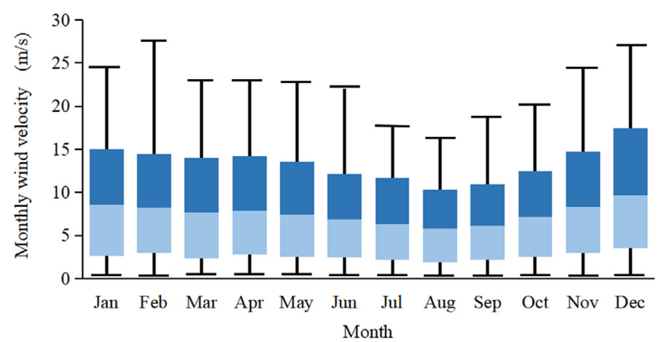

Fig. 4. Wind speed in each month of the year.

5.2.1. Wind energy data

The distribution of wind energy sources in different regions of the earth mainly depends on the wind speed in the region, and then related to the air density over the region (Ulazia et al., 2019). The wind speed data used in this paper are from NASA ground meteorology and solar energy database (Anon., 0000b). The wind speed is taken above 50 m above the earth's surface. The specific wind speed data of the study location in 2020 is shown in Fig. 4 below, which includes the minimum value, the first quartile value, the median value, the third quartile value and the maximum value of each month. It can be seen from the figure, the wind speed in winter is relatively high, about 8–10 m/s; in summer, the wind speed is relatively low, about 5–7 m/s. This is because the air density in winter is higher than that in summer. And low air density and low wind speed in summer lead to low wind power generation.

5.2.2. Energy demand

The energy demand of the platform is mainly electric energy, and the electricity consumption is large. All production and living activities need electric energy support, including water injection system, machine mining system, crude oil processing system, gas treatment system, turbine generator system and the life system. The electricity demand of the platform is shown in Fig. 5. The 92nd day, 153th day and 120th day represent the beginning of summer, mid-season and winter respectively. It can be seen from the figure that the water injection and machine mining system consume the most electricity, and the total electricity consumption in summer is a little higher. The average daily electricity consumption fluctuated little, maintained at about 160 MW.

5.2.3. Technical and cost information on equipment

In this case study, since there is no market or government-recommended economic and technical information of the facilities, project parameters are estimated based on on-site investigation, industry statistics and academic literature, seen in Table 2.

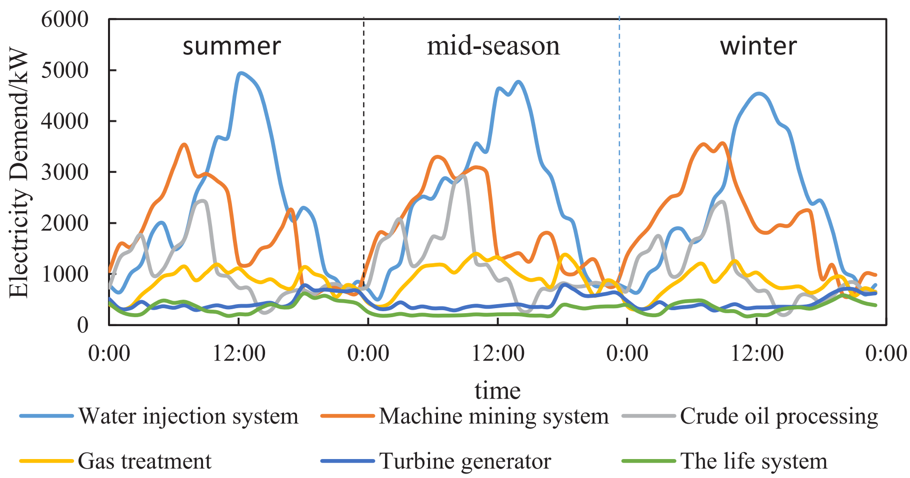

Fig. 5. Daily electricity demand of platform.

Table 2
Parameters of some equipment.

Facility	Linear capacity-dependent cost ($/kW, MWh, kg)	O&M ($/op.hour, year)	Lifetime (year)	Rate of depreciation (%)
Gas turbine engine	300	6	25	80
Wind turbine	550	11	20	80
Converter	45	0	15	80
Battery	210000	1400	20	80
Electrolyzer	142	140	15	80
Hydrogen tank	18.7	1	25	80

Table 3
Device in three systems.

	TES system	WNGN system	WHNGN system
Gas turbine engine	✓	✓	✓
Wind turbine		✓	✓
Converter	✓	✓	✓
Battery	✓	✓	✓
Electrolyzer			✓
Hydrogen tank			✓
Pipeline			✓

Specifically, the lifetime is collected from HOMER Pro's website (Deshmukh and Singh, 2019). The Linear capacity-dependent cost and O&M cost comes from literature Proost (2019) and Yuan et al. (2020).

6. Results and discussion

In this section, the calculation results of the three systems are analyzed and discussed, including economic comparative study, optimal operating strategy, sensitivity analysis and generalization analysis of some countries.

6.1. Economic analysis

By comparing the economic costs of the three systems, the feasibility of the three systems is analyzed. The device of the three systems is shown in Table 3. Traditional TES system include gas turbine engine, converter and battery. Compared with the TES system, WNGN system add the wind turbine. As for the WHNGN system, in addition to wind turbines, electrolyzer, hydrogen tank, pipeline is added too.

The following Fig. 6 is the cost proportion chart of each part of three systems. It can be seen that in the TES system, the cost of gas turbine engine accounts for the majority, about 98%; in the WNGN system, due to the introduction of wind-to power technology, the cost of gas turbine engine is greatly reduced to 13%, at this time, most of the cost is used for wind turbine to generate electricity and battery to storage electricity, account for 23% and 24% respectively; in the WHNGN system, due to the use of hydrogen generation system, excess electricity reduced thus reducing the cost of the battery, at this time, most of the cost is spent on the blending transportation system to transport the hydrogen and natural gas, account for 44%.

When the demand for hydrogen fluctuates, it will affect the development of the whole system. Fig. 7 shows the economic analysis of increasing hydrogen transport capacity from 6000 kg/day to 72000 kg/day. It can be seen from the figure that the NPV of the system increases with the increase of hydrogen transport capacity. When the hydrogen transport capacity is 12000 kg/day, the price of gas sales is higher than the investment cost of the whole system, and the NPV becomes positive. At this time, the introduction of hydrogen generation system will be more economical than no introduction. The next system analysis will take the hydrogen transport capacity of 12000 kg/day as an example.

The income and cost of three systems shown in Fig. 8. It can be seen after the introduction of wind-to-power technology, the electricity generation cost of the system is greatly reduced, which is about 95% lower than TES system. At this time, the total cost is 147 million $, which has achieved a good economic optimization effect. The WHNGN system due to the introduction of hydrogen generation and blending transportation system, although the total cost increases, the NPV of the system becomes positive due to the 208 million$ hydrogen and natural gas sales revenue, the economic benefit optimization result is great.

6.2. Optimal operating strategy

When the wind-to-power technology is introduced to the TES system, 99% of the electricity generation comes from the wind turbine, the natural gas fuel consumption also reduced by 99%. At

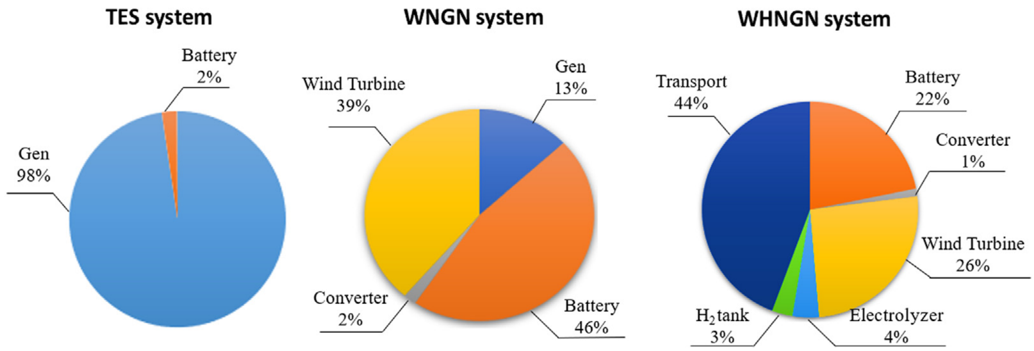

Fig. 6. The cost proportion chart of each part.

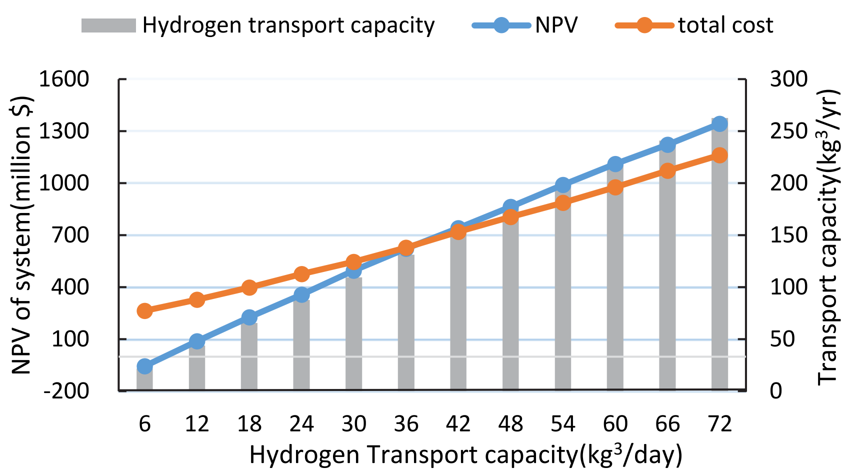

Fig. 7. Economic analysis of different hydrogen transport capacity.

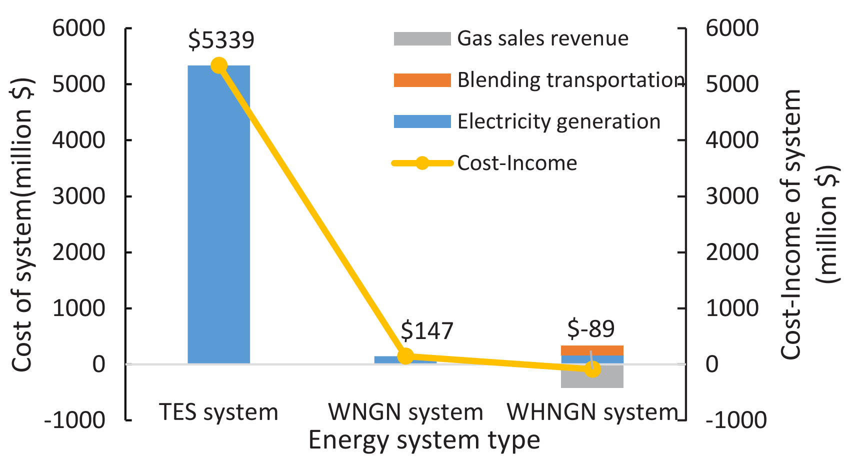

Fig. 8. Economic result of three systems.

this time, the fuel consumption cost and the carbon emission are reduced, which has great economic and environmental benefits. But at the same time, a large amount of excess electricity will be generated. Therefore, hydrogen generation and transportation systems are introduced, excess electricity has been fully utilized, and carbon emissions have also been greatly reduced. In addition, it can be seen from Table 4, levelized energy cost of energy in WHNGN system is the lowest. Therefore, the WHNGN system proposed in this paper is the best in terms of both economic and environmental benefits.

Table 4
Some parameters of three systems.

	TES system	WNGN system	WHNGN system
Excess electricity	0	54%	11.2%
COE ($)	6.83	0.286	0.232
CE (kg/yr)	68,032,597	52,625,293	0

The most important and attractive part of the wind power system is the selection of the optimal wind turbine and the performance of the wind turbine in the wind power system. In this paper, generic 1.5 MW wind turbine is selected as the optimized

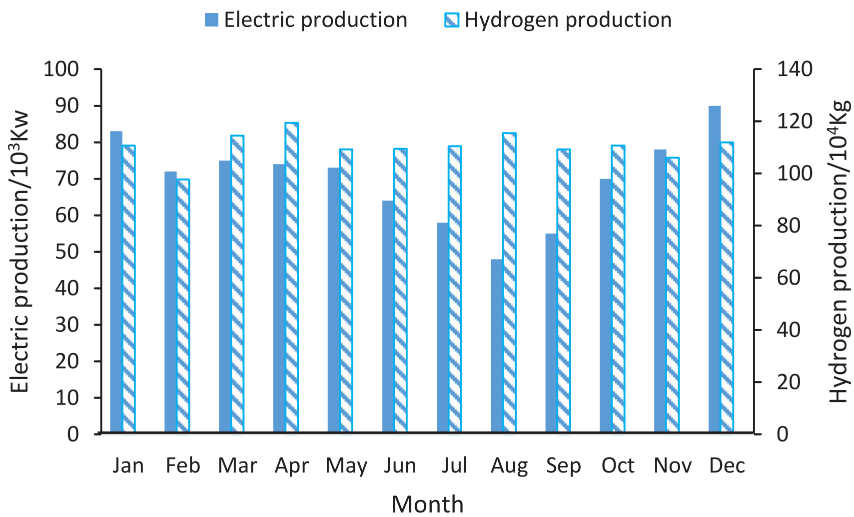

Fig. 9. Wind turbine electricity output and hydrogen production profile.

wind turbine. Fig. 9 shows the output electricity and monthly hydrogen production curve of the generic 1.5 MW turbine. It can be seen from the figure that the monthly power generation is positively correlated with the wind speed. The power generation in winter is significantly higher than that in summer, which is also in line with the rule of higher power demand in winter, while the hydrogen output is stable.

To sum up, we summarize the optimal operation strategy scheme as follow Table 5.

6.3. Sensitivity analysis

Through the above analysis, we can know that the WHNGN system is the most cost-effective. In order to further explore the impact of hydrogen transport capacity and natural gas price on the benefits of the system, a sensitivity analysis model is established.

The wind speed is out of our control, different sea areas will have different wind speed. In order to study the feasibility of the system proposed in this paper under different conditions, a sensitivity analysis was carried out on the influence of wind speed changes on the economy and stability of the system.

Fig. 10 shows the curve of NPV changing with wind speed. The orange line represents the NPV of WNGN system, the blue line represents the NPV of WHNGN system, and the green line represents the difference between the two schemes, that is, the value-added NPV. It can be seen from the figure that the NPV of both systems increases with the increase of wind speed. However, compared with WNGN system, WHNGN system is more sensitive to wind speed. With the increase of wind speed, value-added NPV increases. When the wind speed is greater than 6.3 m/s, the NPV of WHNGN system is positive, and the system begins to generate revenue, and the greater the wind speed, the greater the revenue. At the same time, it can be seen that the slope of the NPV curve decreases when the wind speed is greater than 7.9 m/s, which shows that it is not sensitive when the wind speed is greater than 7.9 m/s.

In addition to the wind speed, for the WHNGN system, the change of gas price also has a great impact on the economy and stability of the system. Fig. 11 is a graph of NPV changing with the selling price of natural gas and hydrogen. The orange line represents the NPV of WNGN system, the blue line represents the NPV of WHNGN system, and the green line represents the difference between the two systems, that is, the value-added NPV. It can be seen from the upper part of the figure that when the selling price of natural gas increases, the net present value of WHNGN system increases, and the growth trend is linear. Only when the price of natural gas is higher than 0.19 $/m^3, the NPV of WHNGN system is positive, and then benefits can be generated. While WNGN system remains unchanged, the same conclusion can be drawn in the lower part of the graph. Compared with WNGN system, WHNGN system is sensitive to gas selling price.

6.4. Generalization analysis of some countries

In order to evaluate the significance of the WHNGN system for energy development in other countries, this section will analyze the economic feasibility of using WHNGN systems in certain countries. The selected countries are shown in Fig. 12, including China, Russia, Kazakhstan, Egypt, Turkey, India, Malaysia and Indonesia, and the selected oil and gas fields locations are also marked.

Due to the different prices of natural gas and hydrogen, equipment and wind speed in different countries, the calculated NPV is also different. The input data is shown in Table 6.

The result is shown in Fig. 13 below. It can be seen from the figure that the NPV of China, Kazakhstan, Turkey, India, Malaysia and Indonesia has increased with the increase of hydrogen and natural gas transportation, which shows that the system is applicable to these six countries. However, the NPV of Russia and Egypt is always negative, indicating that the system cannot bring profit, and this system is not feasible. We can infer that the wind speed has little effect on the system NPV, the main reason for this phenomenon is the relatively low selling prices of natural gas in Russia and Egypt, the selling price of hydrogen and natural gas is lower than the operating price of the equipment, so the NPV is negative and the system is not feasible.

7. Discussion

The WHNGN system proposed for the offshore oil and gas fields development in this paper has the potential to concurrently reduce carbon emissions, increase profits, and increase the renewable energy utilization. Taking an oil and gas field in Bohai Bay as an example, from the calculation results in Fig. 8, it can be seen that compared with the traditional TES system, the WHNGN system can bring additional economic benefits of 417 million $ while reducing costs by 6.011 billion $ in 25 years, and according Table 4, the carbon emissions decrease 68,032,597 kg/year,

Table 5
Techno and financial specification of the best strategy.

Specification	Equipment and indexes				
System architecture	Wind turbine Generic 1.5 MW	Generator 1500 KW	Converter 60,000 KW	Battery 1MWh Li-Ion	H_2 Tank 400,000 kg
Financial ($)	Initial capital 135,391,864 Transmission cost 145,412,400	Operating 64,305,956 Selling price 417,414,000	COE($/kW h) 0.232 Total cost 328,284,600	Fuel 0 NPV 89,129,400	Salvage 16,825,650
Electrical production (KWh/yr)	Wind turbine 331,035,115	Generator 0	AC primary load 61,017,021	Excess electricity 37,080,690	
Hydrogen system (kg/yr)	Electrolyzer production 4,716,590		Unmet hydrogen load 0		
Pollution	CO_2 0				

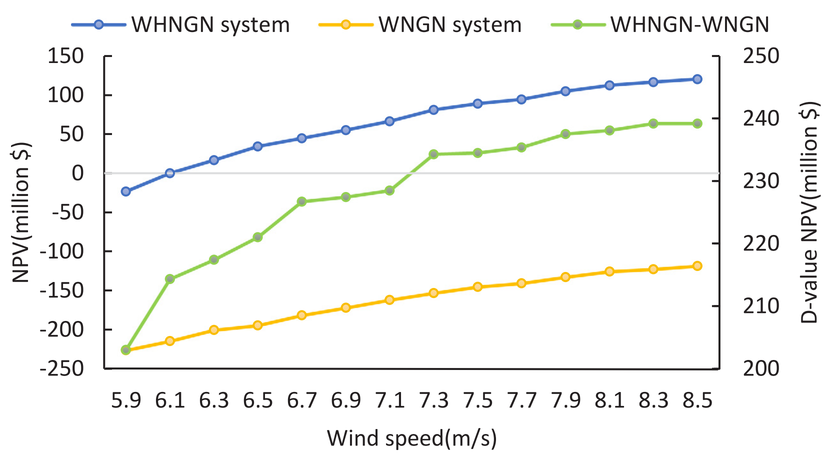

Fig. 10. Sensitivity analysis of wind speed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 6
Input data for different countries.

	Average wind speed (m/s)	Natural gas price ($/m^3)	Hydrogen price ($/kg)	Location	Year
China	7.41	0.26	0.90	39°52′N 119°95′E	2020
Russia	8.10	0.04	0.14	70°02′N 51°25′E	2020
Kazakhstan	7.80	0.36	1.25	46°26′N 52°81′E	2020
Egypt	7.14	0.11	0.38	31°36′N 28°11′E	2020
Turkey	7.25	0.38	1.32	44°33′N 31°14′E	2020
India	6.43	0.49	1.70	3°26′N 2°28′E	2020
Malaysia	6.01	0.24	0.83	3°07′N 111°29′E	2020
Indonesia	6.37	0.37	1.28	3°91′N 120°04′E	2020

not only has great economic benefits, but also has good environmental benefits.

The main factors affecting the stability of WHNGN system are wind speed and gas selling price. From the results in Figs. 10 and 11. We can infer that when the wind speed and gas selling price are too low, it is not economical to use this system.

Based on the above analysis and discussion, some management recommendations are given to better elaborate how this system strategy could be further used in real application. For the government, it is necessary to formulate corresponding policies to encourage the establishment of renewable energy power generation systems to achieve clean electricity future. Studies have proven that the use of renewable energy can increase corporate income and reduce the use of fossil fuels. Although the renewable energy power generation system has been touted by researchers and engineers around the world, its efficiency has not yet reached expectations. Therefore, the government needs to develop focused policies and regulations to encourage wider recognition of the establishment of the system. In addition, for the wind and hydrogen energy industries, it is also necessary to consider the improvement of installed capacity and new technologies to explore better performance.

8. Conclusions

This paper takes the offshore oil and gas field energy system as the research object, motivated by economic and environmental aspects, raises the WHNGN system to make offshore oil and gas field more profitable, including oil and gas production system, electricity generation system, hydrogen generation system and blending transportation system. Using the energy supply system design MILP model, economic and environment evaluation model, this paper compares the techno-economic feasibility of TES, WNGN and WHNGN systems, and determines the prefer system scheme.

The advantages of WHNGN system are illustrated by comparing three system schemes. Take an offshore oil and gas field in Bohai Bay as an example, the final optimization design and operation scheme of the system are analyzed, and the economic configuration of WHNGN system is introduced in detail. Finally,

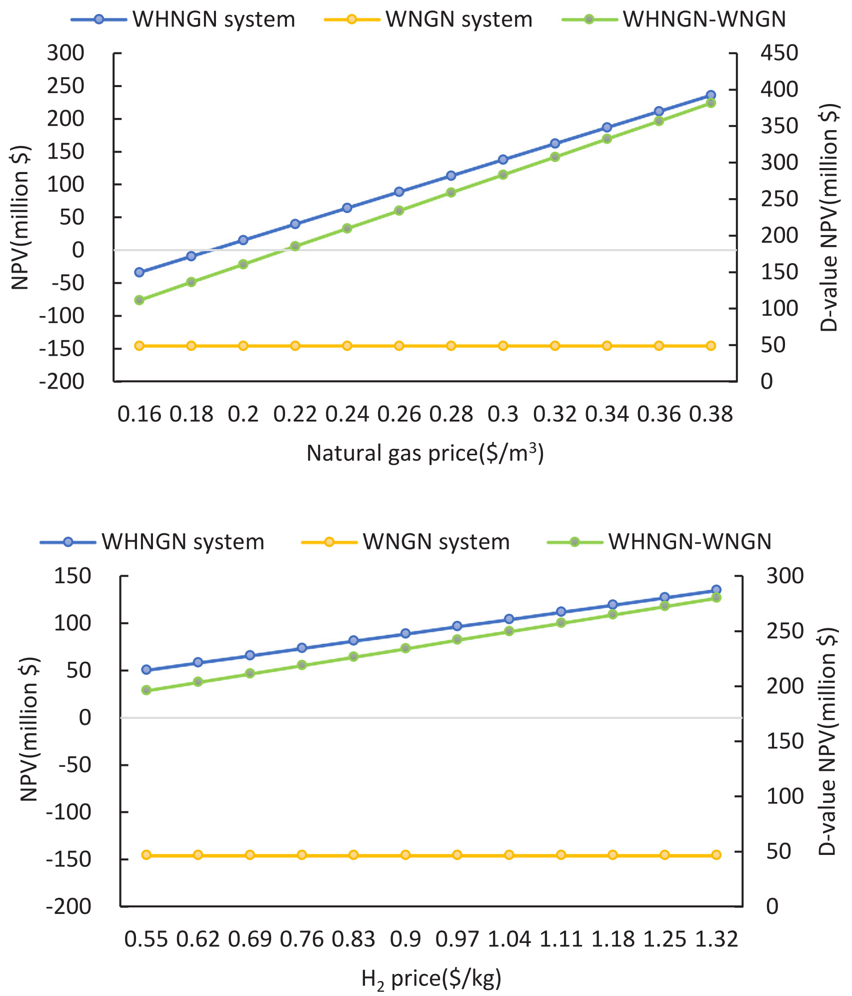

Fig. 11. Sensitivity analysis of gas selling price. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 12. The geographical location of the selected oil and gas fields.

a series of sensitivity analysis is done to make a more detailed analysis of the system.

Our primary conclusions are as follows.

(1) Compared with the traditional TES system, the WHNGN system can bring additional economic benefits of 417 million $ while reducing costs by 6.011 billion $ in 25 years.

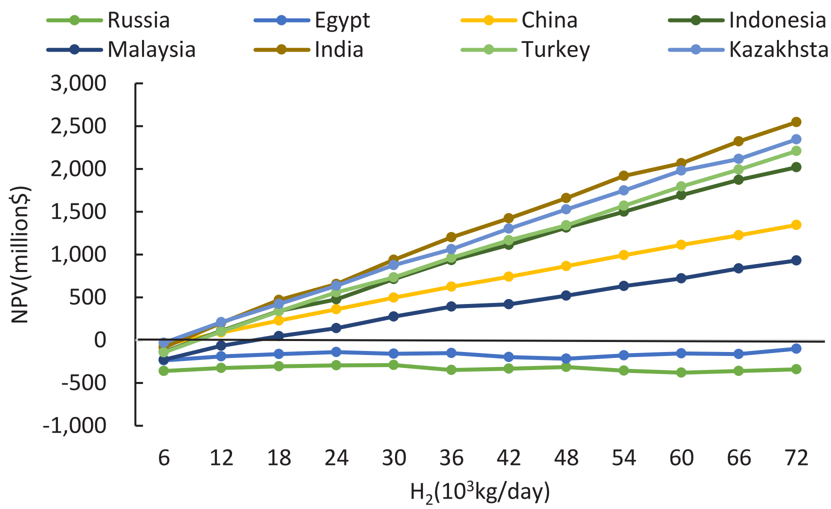

Fig. 13. Generalization analysis of some countries.

(2) The WHNGN system can effectively use clean energy, reduce carbon emissions by 68,032,597 kg/year, not only has great economic benefits, but also has good environmental benefits.

(3) Compared with the WNGN system of independent power generation, WHNGN system makes full use of the excess electricity, not only brings additional economic benefits, but also greatly alleviates the problem of wind abandonment.

(4) Through the sensitivity analysis of the WHNGN system, it is found that the greater the wind speed, the more significant the economic benefits, and the gas sales price also has a certain impact on the system. The higher the selling price of natural gas, the better the economic benefits.

(5) Through the generalization analysis of some countries, it is concluded that China, Kazakhstan, Turkey, India, Malaysia and Indonesia can use the WHNGN system because of the high selling price of hydrogen and natural gas.

In summary, using wind energy to electricity supplying of offshore oil and gas oilfields is a feasible option. By using the wind energy to electricity supplying, reducing their carbon footprint by shutting down the gas turbines running on fuel diesel, improves the economy and environmental of the field by avoiding the use of diesel fuel, which is a valuable source of energy in remote locations. In addition, it is also feasible to use excess electricity to produce hydrogen and blending transported it with natural gas for sale in locations with high gas sales prices. Through it, the wind electricity curtailment problems in wind power development is well solved, at the same time, it also brings great economic benefits.

The WHNGN system can promote the development of offshore wind and hydrogen energy, and being a competitive solution to replace the gas turbines, mainly for aging fields that have already all or some of the gas turbines running using diesel. The techno-economic analysis method proposed in this article to determine whether the WHNGN system should be applied in areas with certain wind conditions and in existing offshore oil and gas fields. And can be used to find the optimal size for any location, help investors quantify economic and environmental benefits, determine the scale of hydrogen production and blending transportation plan. Future work should proceed from a broader perspective, including the joint power supply of multiple renewable energy sources and the overall optimization of hydrogen production and the hydrogen supply chain.

Nomenclature

BT	Battery
CE	Carbon emission
COE	Cost of energy
CV	Converter
ET	Electrolyzer
GT	Gas turbine
HT	Hydrogen tank
MILP	Mixed Integer Linear Programming
NPC	Net present cost
NPV	Net present value
O&M	Operation and maintenance
TES	Traditional energy supply
WHNGN	Wind–hydrogen–natural gas nexus
WNGN	Wind–natural gas nexus
WT	Wind turbine

CRediT authorship contribution statement

Xueqing Zou: Conceptualization, Formal analysis, Validation and Original draft preparation. **Rui Qiu:** Methodology, Validation and Writing - Reviewing. **Meng Yuan:** Writing - Reviewing and Editing. **Qi Liao:** Investigation, Data Curation and Visualization. **Yamin Yan:** Formal analysis and Check. **Yongtu Liang:** Supervision and Funding acquisition. **Haoran Zhang:** Conceptualization, Methodology.

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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