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OPTIMIZING THE USAGE OF RENEWABLE ENERGY FOR POWERING OFFSHORE OIL FIELDS

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ABSTRACT

Carbon dioxide (CO_2) emission due to power generation from fossil fuel is a major contributor to the current issues of global warming and climate change. This paper proposes offshore generation of electricity from renewables to supply offshore oil fields. An existing oil field in the UK North Sea was assumed and a hybrid power system consisting of power from wind, wave, and fossil fuel generators was dedicated to it. The feasible/economical reduction in CO_2 emission was investigated by using Homer Pro software to model and simulate performance of the micro-grid. Data of the renewable resources are specific to the selected site. From the simulation results, a solution with the lowest net present cost (winning system) was chosen and compared with the base case system to observe how the hybrid system saves cost over the project lifetime. The winning system was refined as much as possible to develop the optimal system which was proposed for implementation. This system demonstrated its economics relative to the base case system as the annual fuel consumption and the corresponding CO_2 emission dropped by 38% each. Likewise, the cost of energy fell by 42%. Imposition of carbon tax was recommended to boost the development of renewables.

Keywords: *Renewable Energy, Offshore Oil Field, Climate Change, CO_2 Emission, Carbon Tax*

INTRODUCTION

Offshore drilling for extraction of crude oil and natural gas from seabed has many advantages over the onshore approach. Offshore oil fields are less prone to sabotage and theft, among other benefits. Meanwhile, the activities in offshore oil fields involve a range of power, control, and monitoring operations which require constant supply of power [David Toke, 2019]. The involvement of unmanned underwater machines as well as domestic energy needs of the residing workers, made these oil fields more energy intensive than the onshore types. However, powering offshore oil fields is limited by a series of constraints most of which are due to its location. Traditionally, the required power is provided via platform-based generation by the use of diesel engines, but the associated CO_2 emission contributes immensely to the issues of climate change [Husdal, G., 1994]. Substituting diesel fuel with natural gas, in combined-cycle power plants, does not really eradicate emission of greenhouse gases because the burning of fossil fuel is still involved. Globally, offshore oil fields release about 200 million tonnes of CO_2 annually as of January, 2018 [Pal, K., 2020].

Many approaches have been proposed to reduce the CO_2 emission caused by power generation entirely. These include generating power from renewable sources, energy management, and the use of bio-fuels or low-carbon fuels like bio-methane or hydrogen. Implementation of carbon dioxide enhanced oil recovery (CO_2 EOR) technique, as well as regular monitoring of CO_2 emission are some of the developed approaches specific to emission from the hydrocarbon industry [Marit J.M.,, et al., 2014]. Minimizing power requirement was proposed by Cadigan, M.F., and Peyton, K. [2005] as a more cost-effective way to reduce carbon footprint of oil fields. The energy needed for a given production volume reduces with efficient drilling operations. This can be achieved by improving the power factor of energy-intensive equipment.

Energy consumed in heating the rooms and offices can be reduced by considering wind drag at the design stage of new oil platforms, while for existing platforms, electrical heaters or steam boilers can be replaced with innovative waste heat recovery units [Kloster, P., 1999]. In situations where the drilling platforms float, the type of heave compensation system used to reduce the influence of waves also affects energy consumption [Liu, S., et al., 2020]. Minimizing the time for a given task and proper positioning of drilling rigs are common strategies for energy management in well drilling [Norman J.H., 2021]. Unfortunately, each of these laudable ideas has its own challenges.

Based on its environmental benefits, the CO_2 EOR technique looks like a breakthrough but carbon capture systems need to be installed at manufacturing facilities and power plants, together with pipelines to convey the carbon dioxide to the oil field [George P., 2010]. The CO_2 needs to be permanently sequestered in the oil formation after completion of EOR activities. Restricting the CO_2 from going back into the atmosphere is a research in progress [Ramharack, R.M., et al., 2010]. Further engineering and scientific facts about geologic sequestration is also needed to establish appropriate long term CO_2 monitoring programs. The need for separation or clean-up before being stored underground, adds to the cost of carbon storage. According to Diana, H., et al. [2015], Chevron has built a carbon capture and storage project in Australia to minimize its own emission by capturing up to four million tonnes of CO_2 annually. Carbon capture, usage, and storage (CCUS) is vital in achieving net-zero emissions for the planet to attain climate goals. Although, the huge capital investment and required technology may not support economic operation of the system. On the other hand, renewable energy is fundamentally a free energy that exists in different forms, but the costs incurred in its conversion is sometimes discouraging. This could be responsible for the low percentage of world energy presently generated from renewables as depicted in Fig. 1.

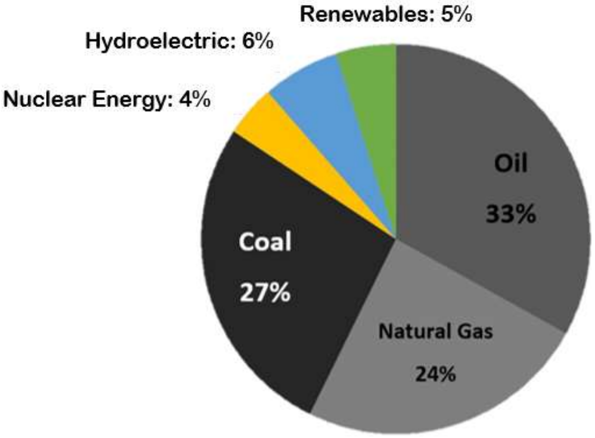

Fig. 1. Primary Energy Consumption 2019 (BP Statistical Review 2020)

Other impediments to the growth of renewable energy include not having the resources at all time, in every place, and in the needed quantity. The required space and associated environmental inference are other concerns. Space on land is limited and needed for agriculture, housing, roads, industry, and recreation among others. Allocating a portion of these scarce resources to wind or solar farms is usually a constraint. Uncertainty about sustainability when it comes to generating power up to hundreds of MegaWatts was identified by David, J.C. MacKay [2008] as a reason why this green initiative has not been well embraced by the oil and gas authority, especially for powering offshore oil rigs.

In addition to the emission concerns, powering offshore oil fields via fossil fuel is not economical as about 5% of offshore wellhead daily production globally is burnt to power the platforms [Qiu, Z., et al., 2016]. This not only reduces the sales volume but also has an indirect impact on oil production cost. Likewise, the generators and power equipment needed are built with expensive materials and coatings in order to withstand the saline, wind, moisture, and temperature of the environment. The noise and vibrations from fossil fuel generators, coupled with the effects of extra weight are undesirable especially for the floating platforms. The need for sending boats in to deliver fuel, as well as engaging workers in fuel supply are other hitches of powering offshore oil fields via fossil fuel. The subsequent costs and hazards are quite discouraging. Powering oil fields via renewables would help meet the net-zero carbon target. It also extends the production life of oil fields and reduces oil production cost [David, J.C. MacKay, 2008].

METHODOLOGY

To investigate the feasible and economic reduction in CO_2 emission from offshore oil fields, a micro-grid dedicated to an assumed oil field was modelled using Homer Pro Software. The grid is a standalone hybrid power system with power generated offshore via renewables (wind and wave) and fossil fuel generators. The assumed oil field is located in the British sector of the North Sea. One of the reasons for choosing the North Sea is that it has the highest number of offshore oil and gas infrastructures worldwide. Thus, when the oil field powered by the proposed micro-grid is eventually decommissioned, having attained end of its production life, re-routing the power to a neighbouring oil field could be done at minimal cost. Another reason is that the wind and wave resources are considerably abundant in the North Sea. As a guide to economic feasibility study, some existing wind farms in the UK North Sea were examined in terms of water depth, distance to the shore, project capacity and cost, amongst others. (Appendix A). Similarly, in order to choose a practical location for the assumed oil rig, some existing offshore oil platforms in the UK North Sea were considered (Appendix B). It was realized that while the wind farms are nearer to the shore, the oil fields are farther away. However, locating the micro-grid very close to the oil field minimizes power loss and reduces costs in terms of the required power transmission equipment.

This study involves a deep-water wind farm because the wave resource is more prominent far away from the shore and the oil field to be powered is equally faraway. Water depth is thus a critical economic factor in siting offshore wind farms when the turbines are to be sea-bed tied. With these considerations, the proposed micro-grid is at 100 kilometers north-east of Aberdeen (Central North Sea) in an approximate water depth of 100 meters. This is the position of Buzzard oil field, hence an assumed oil and gas platform in this location can be quite realistic. The utilized data of renewable resources (wind and wave) are specific to this selected location.

Power Demand of the Oil Field

Modelling a micro-grid requires information about the load to be powered. Oil and gas extraction involves numerous operations whereby large electric motors are being used. Unlike their land-based counterparts, offshore oil fields demand more power due to the involvement of unmanned underwater machines, accommodation facilities, and the harsh weather, among others. Size of the oil field (number of oil blocks), as well as the number of oil production wells in operation generally influence the energy consumption, because they determine the amount of water (or gas) injection facilities needed. Energy consumption data of oil fields is not publicly available at this moment. Thus, an estimation of the load was made from ratings of commonly used equipment (Table 1).

Powering the wellhead involves well-drilling and lifting of production fluids to the well surface. These are energy intensive tasks in oil fields. The equipment/machines needed here are mainly for compression and pumping operations. Power demand for the seabed infrastructures were assumed (being insignificant relative to that of the wellhead), while load of the living quarters were projected based on average demand of a typical one-bedroom apartment. With a total load of 14 MW, maximum demand of the oil field was approximated to 10 MW using a demand factor of 0.7. Generally, electric loads vary with time of the day and season of the year as ambient temperature changes.

Table 1: Estimated Load of the Oil Field

#	Equipment	Application	Rating (kW)	Assumed Unit	Load (kW)
1	Shale Shaker	Cleaning of the drilling mud for reuse.	45	5	225
2	Mud Agitator	To suspend solids and maintain a homogeneous fine mixture.	24	3	72
3	Atmospheric (Poor Boy) Degasser	Reducing risk of gas explosions by removing air and gases trapped in the drilling fluid.	8	2	16
4	Drilling Mud Pump	The heart of mud circulation system.	1275	6	7650
5	Electrical Flare Ignitor	Burning of the waste gases captured by mud gas separator.	1	2	2
6	Vertical Cuttings Dryer	Minimizes volume of drilling cuttings disposed.	57	2	114
7	Sand Pump	For cleaning oil or fluid tanks by carrying particles away.	56	3	168
8	Drill Rotary System	Boring holes into the sea-bed.	746	3	2238
9	Electric Submersible Pump (ESP)	Artificial Lifting of production fluids to the surface.	373	8	2984
10	Wellhead Compressors	Increasing the pressure of compressible fluid.	56	6	336
11	Seabed infrastructures	Control, monitoring, and provision of communication among relevant equipment.	75	-	75
12	Lighting, Heating and Cooling Systems	Illumination, preparation/preservation of food, room temperature control, etc.	3	40	120
				Total:	14000

Therefore, designing an off-grid power system requires data of the variation in load against time (load profile). This helps in planning how much power to be made available at every given time such that excess generation can be minimized as much as possible without failure to meet the load at any instant of time. The assumed hourly load profile of the oil field is as given in Fig. 2. Due to unavailability of data, the load profile was assumed to be fixed and represents the typical energy consumption per day in winter months where peak demand occurs.

Renewable Resources

Proportion of the load that can be powered via renewables depends on extractable power by the wind turbines and wave energy devices on the site. This is a function of the available resources because the power output of a wind turbine depends on the wind speed, while that of a wave energy converter (WEC) is subject to the wave height and period.

Data of these resources for the selected site were obtained from different sources for the purpose of validation through comparison. Data were collected from the National Renewable Energy Laboratory (NREL), as well as the National Aeronautics and Space Administration (NASA). Table 2, shows the monthly average wind speed in the site at 50 m above ground with an annual average of 9.17 m/s. These data are fed into Homer Pro to simulate the performance and economic feasibility of a wind farm in the specified location.

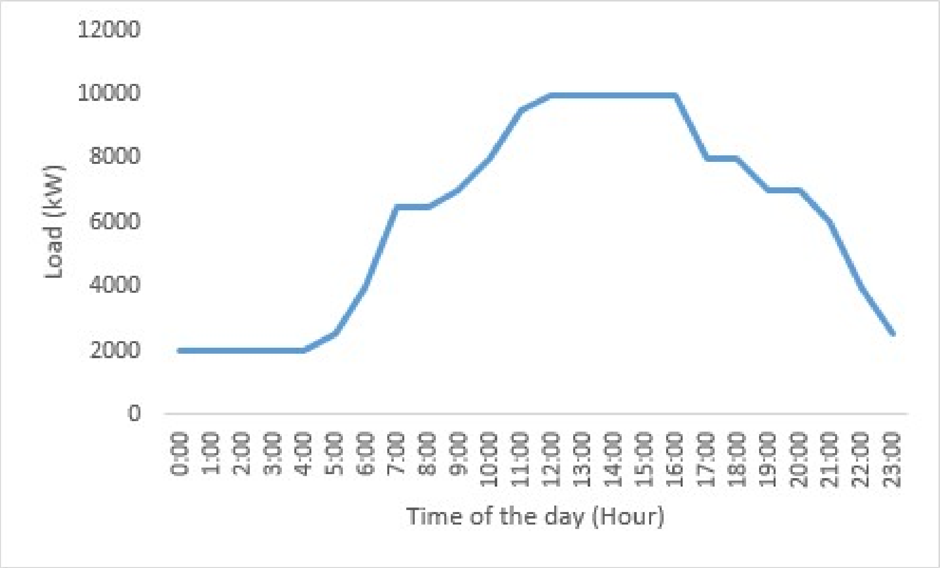

Fig. 2. Load Profile of the Oil Field

The procedure was slightly different for the wave power because there is no interface for direct input of wave data in the available software version. Consequently, extractable power from the sea waves was estimated theoretically and then added to the model as a renewable power source. Similar energy modelling software such as the System Advisor Model (SAM), or RETScreen Expert could have been used in this study, but Homer Pro was utilized based on availability and its flexibility.

Wave Power in the Site

It is important to reiterate that this study is considering deep-water (depth greater than half the wavelength) waves and real sea states where there is interaction of many waves of different lengths originating from different directions at any instant. The speed, v (in m/s) at which the wave is travelling can be expressed as:

$$v = \frac{\lambda}{T} \tag{1}$$

Table 2: Wind Resource

#	**Month**	**Average Wind Speed (m/s)**
1	January	11.48
2	February	10.83
3	March	10.03
4	April	8.39
5	May	7.65
6	June	7.25
7	July	7.02
8	August	7.47
9	September	8.62
10	October	9.99
11	November	10.60
12	December	10.73

[https://www.windfinder.com/forecast/]

Where: λ is the wavelength, and T (period) is the time taken to travel a wavelength. This expression indicates that longer waves travel faster than shorter ones. In deep-water, the acceleration, g (product of angular velocity and speed) is due to gravity and it is expressed as:

$$g = \omega v \tag{2}$$

$$v = \frac{g}{\omega} \tag{3}$$

The angular velocity, $\omega = 2\pi f$ (4)

Where: frequency, $f = \frac{1}{T}$

Thus, $\omega = \frac{2\pi}{T}$ (5)

Substituting (5) into (3) gives:

$$v = \frac{gT}{2\pi} \tag{6}$$

However, waves travel in groups across the sea surface with a group velocity u, which is half the wave velocity. In other words, the velocity for a set of waves is given by:

$$u = \frac{gT}{4\pi} \tag{7}$$

The total energy, E possessed by the wave of amplitude a, in a water of density ρ, is the sum of its kinetic energy, E_k and potential energy, E_p per unit width of wave front, per unit length of wave.

$$E = E_k + E_p \quad (\text{But, } E_k = E_p)$$

$$E = \frac{1}{4}\rho g a^2 + \frac{1}{4}\rho g a^2$$

$$E = \frac{1}{2}\rho g a^2 \tag{8}$$

If H represents peak-to-peak height of the wave, then:

$$a = \frac{H}{2} \tag{9}$$

Substituting (9) into (8) gives:

$$E = \frac{1}{8}\rho g H^2 \tag{10}$$

Power, P is the energy passing a point in one second. Thus, the power contained in a set of waves is a product of the energy and group velocity.

$$P = \frac{1}{8}\rho g H^2 \left(\frac{gT}{4\pi}\right)$$

$$P = \frac{\rho H^2 g^2 T}{32} \tag{11}$$

For a given site, only H and T varies. Hence, the estimated maximum possible power in kiloWatt per meter (kW/m) of wave front is:

$$P \approx H^2 T \tag{12}$$

The hourly significant wave height (H_{sig}) and average period in the site as reported by the National Data Buoy Center (NDBC) was used to estimate the average wave power for each month of the year as given in Table 3.

***Table 3:* Wave Resource**

Month	**Average H_{sig} (m)**	**Average Period (second)**	**Average Power (kW/m)**	**Converter Output (kW)**
Jan.	1.59	6	15.17	53.25
Feb.	1.53	4	9.36	32.85
Mar.	1.41	5	9.94	34.89
Apr.	1.30	6	10.14	35.59
May	1.23	4	6.05	21.24
Jun.	1.18	4	5.57	19.55
Jul.	0.96	5	4.61	16.18
Aug.	1.15	5	6.61	23.20
Sep.	1.24	5	7.69	26.99
Oct.	1.39	4	7.73	27.13
Nov.	1.48	5	10.95	38.43
Dec.	1.55	6	14.42	50.61
Average:	**1.33**			**31.66**

[https://www.metoffice.gov.uk/research/weather/ocean-forecasting/ocean-waves]

Average power in the month of January was obtained as follows:

$$P = H^2 T = (1.59)^2 * 6$$

$$= 15.17 \text{ kW/m of wave front}$$

Wave Energy Conversion

A wave energy converter (WEC) is needed for extracting the power contained in sea waves. There are several technologies used for wave energy conversion. The sea state generally determines the suitable type and size of WEC to be deployed. This study is however considering the Pelamis device, being the most advanced commercially implemented technology so far. Surface area of the Pelamis determines the amount of power it will be able to extract for a given wave resource. In accordance with the annual average significant wave height of 1.33 m (Table 3), the Pelamis device can have a diameter of 1.3 m. This it implies that every section will be interacting with 1.3 m of wave front. Thus, the power available to each section of the device is estimated as:

$P = 15.17 \text{ kW/m} * 1.3\text{m} = 19.721 \text{ kW}$

Assuming the proposed device consists of four sections, whereby three of them interact with the wavelength at a time, power available to the device would be:

$P = 19.721 \text{ kW} * 3 = 59.163 \text{ kW}$

If the converter is 90% efficient, average output power, P_o in the month of January is:

$P_o = 59.163 \text{ kW} * 0.9 = 53.25 \text{ kW}.$

With the average annual power output of 31.66 kW (Table 3), an array of ten units of 40 kW wave energy device was proposed.

System Modeling and Simulation

An efficient hybrid power system is one that operates with the least carbon footprint and cost. Thus, modelling of the micro-grid is aimed at optimizing the penetration of renewables into the power system in order to minimize fuel consumption and its effects. However, due to the erratic nature of renewable resources, an off-grid hybrid power system should have provision for a situation whereby the load has to be exclusively powered via fossil fuel. Such a non-renewable power system is regarded as the fuel-based scenario. In this situation, energy cost is significantly affected by fuel consumption and price. The former primarily depends on load level, energy density of the fuel, and efficiency of the internal combustion engine. Appendix C gives the approximate fuel consumptions, in litres per hour, at different load levels for various sizes of diesel generators as published by FW Power (a specialist generator company). The natural gas equivalent is in Appendix D. The estimated fuel consumptions are based on the assumption that all generators have a fixed revolution per minute (RPM).

To power the oil field solely via fossil fuel, 14,000 kW generator was suggested to meet the peak load of 10,000 kW such that no generator is loaded above three-quarter of its capacity. Fourteen units of 1 MW generator were proposed in order to lessen the effects of breakdown/shutdown during maintenance. This idea also ensures even distribution of weight across the platform and reduces the battery capacity needed for storing energy in periods when generation is greater than demand. Other consequences of generating excess power are equally reduced. The approximate fuel consumption for 1 MW diesel generator is 194 litres per hour at $\frac{3}{4}$ full load (Appendix C). This implies that 194 litres of diesel is needed to generate 750 kW of power for one hour. Table 4(a) shows the daily diesel fuel consumption for the load profile of Fig. 2 and the number of 1 MW generators running at a given time. The natural gas equivalent is given in Table 4(b) and a fixed load level is assumed in either case.

Greenhouse gas emission is often influenced by the volume of fossil fuel burnt. In particular, CO_2 emission is affected by the mass per unit volume of the fuel. This mass indicates the proportion of carbon in the fuel and the corresponding amount of oxygen needed for complete combustion of the fuel. The discrepancy in carbon content of fossil fuel is responsible for varying amounts of CO_2 emission from equal volume of the fuel.

Table 4(a): **Diesel Usage at $\frac{3}{4}$Full Load**

Time of the Day	Load (kW)	No. of Gen.	Diesel (Litre)
0:00 - 1:00	2000	3	582
1:00 - 2:00	2000	3	582
2:00 - 3:00	2000	3	582
3:00 - 4:00	2000	3	582
4:00 - 5:00	2000	3	582
5:00 - 6:00	2500	4	776
6:00 - 7:00	4000	6	1164
7:00 - 8:00	6500	9	1746
8:00 - 9:00	6500	9	1746
9:00 - 10:00	7000	10	1940
10:00 - 11:00	8000	11	2134
11:00 - 12:00	9500	13	2522
12:00 - 13:00	10000	14	2716
13:00 - 14:00	10000	14	2716
14:00 - 15:00	10000	14	2716
15:00 - 16:00	10000	14	2716
16:00 - 17:00	10000	14	2716
17:00 - 18:00	8000	11	2134
18:00 - 19:00	8000	11	2134
19:00 - 20:00	7000	10	1940
20:00 - 21:00	7000	10	1940
21:00 - 22:00	6000	8	1552
22:00 - 23:00	4000	6	1164
23:00 – 0:00	2500	4	776
Diesel Fuel Consumed per day:			**40,158**

To model the power system, all the required engineering and cost data were entered into the respective input windows in the software. These include information about the site location, the load profile, and data of the renewable resources (wind and wave) in the site. The system converter, battery storage, and the thermal load controller (TLC) were selected based on the peak load and possible excess generation. Diesel generator was then added to the model to form a hybrid system. +++++Natural gas generator was later used as a replacement for the diesel generator.

Table 4(b): **Gas Usage at $\frac{3}{4}$Full Load**

Time of the Day	Load (kW)	No. of Gen.	Natural Gas (m^3)
0:00 - 1:00	2000	3	861.99
1:00 - 2:00	2000	3	861.99
2:00 - 3:00	2000	3	861.99
3:00 - 4:00	2000	3	861.99
4:00 - 5:00	2000	3	861.99
5:00 - 6:00	2500	4	1149.32
6:00 - 7:00	4000	6	1723.98
7:00 - 8:00	6500	9	2585.97
8:00 - 9:00	6500	9	2585.97
9:00 - 10:00	7000	10	2873.30
10:00 - 11:00	8000	11	3160.63
11:00 - 12:00	9500	13	3735.29
12:00 - 13:00	10000	14	4022.62
13:00 - 14:00	10000	14	4022.62
14:00 - 15:00	10000	14	4022.62
15:00 - 16:00	10000	14	4022.62
16:00 - 17:00	10000	14	4022.62
17:00 - 18:00	8000	11	3160.63
18:00 - 19:00	8000	11	3160.63
19:00 - 20:00	7000	10	2873.30
20:00 - 21:00	7000	10	2873.30
21:00 - 22:00	6000	8	2298.64
22:00 - 23:00	4000	6	1723.98
23:00 – 0:00	2500	4	1149.32
Natural Gas Consumed per day:			**59,477.31**

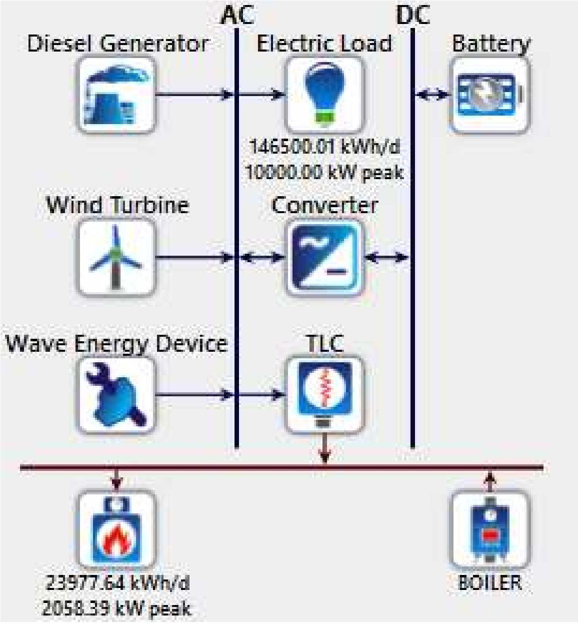

Fig. 3. System Schematic

Homer is an economic model hence, cost information is central to its analysis. In other word, accuracy of the result is based on cost precision. However, the cost data used were based on previously executed projects and prices from manufacturers' websites. The Homer optimizer tap was selected in every input window to optimize the penetration of renewable energy into the power system. The simulation engine in Homer runs in hour-by-hour time step for a full year. At each of these time steps, Homer selected the most cost-effective configuration to meet the load.

From the simulation results, a solution with the lowest net present cost (NPC), often referred to as the winning system, was chosen and compared with the base case system to observe how the hybrid system saves money over the project lifetime. Finally, sensitivity analysis which is the most critical aspect of the modelling was performed. It is a form of risk analysis that makes it possible to examine what happens if any of the uncontrollable variable's changes. Such sensitivity variables include fuel price and energy storage cost. Sensitivity analysis was also performed to examine the impact of controllable variables on the power system. The fuel type (diesel/gas), hub height of the wind turbine, and converter type are examples of such sensitivity variables. The winning system was refined as much as possible by altering the sensitivity variables to develop the optimal system proposed for execution.

RESULTS AND DISCUSSION

As of September 2021, a litre of diesel fuel in the UK costs £1.35. However, about 80% of this retail price is due to fuel duty, value added tax (VAT), retailer's profit, etc. Therefore, a litre originally costs about £ 0.27. However, fuel expense depends on energy density of the fuel which ranges from 32 to 40 MegaJoules (MJ) per litre of diesel. A kiloWatt-hour (kWh) is 3600 kiloJoule (kJ). If a litre of diesel contains 36 MJ, it implies that one litre is 10 kWh. But, the efficiency of conversion into kinetic energy is about 30 percent. Hence, a litre of diesel is equivalent to 3 kWh and the fuel cost per kWh is £0.09. With the daily demand of 146,500 kWh (Table 4), fuel expense for the oil field is over £ 4.8 million annually. In addition, energy from diesel costs 0.00075 pence per kJ.

Table 5: **Power and Energy Data**

Power (kW)	Duration (h)	Energy (kWh)
2000	5	10000
2500	2	5000
4000	2	8000
6000	1	6000
6500	2	13000
7000	3	21000
8000	3	24000
9500	1	9500
10000	5	50000
55500	**24**	**146500**

On the emission aspect, a litre of an average quality diesel fuel produces 2.772 kg of CO_2 [David, J.C. MacKay, 2008]. This implies that the CO_2 emission from diesel fuel is 0.924 kg per kWh. More than 49 thousand tonnes of CO_2 is released every year as about 20.3 GigaWatt (GW) is generated annually to power the oil field (Table 4). Cumulatively, about 593 thousand tonnes of CO_2 is emitted yearly from the oil fields in Appendix B if each of them demands the same amount of energy. Similarly, the average retail price for one cubic meter (m^3) of natural gas is about £0.50 as of September 2021. If the VAT, fuel duty, and other costs are excluded, the price falls to £0.10/m^3 (80% decrease). Natural gas produces lesser emission relative to diesel fuel because it has higher energy density. If a normal cubic meter (m^3) of natural gas contains 37 MJ of energy, it implies that energy equivalent of this fuel is 10.28 kWh/m^3.

However, the efficiency of conversion of natural gas into electricity depends on the type of plant used. It is about 33% in vapour electric plants (steam turbines), but ranges from 50% to 60% in combined-cycle power plants. If the conversion efficiency is 50%, 1 $m^3$of natural gas would give 5.14 kWh and fuel cost per kWh is about £0.02.

In addition, energy from natural gas apparently costs 0.00027 pence per kJ which is only 36% of equivalent cost when diesel fuel is used. In simple terms, energy from natural gas is quite cheaper than the one from diesel fuel. A difference of £0.07 per kWh can be seen in this situation. If 146,500 kWh is being consumed per day (Table 4), fuel expense of the oil field reduces to about one million GBP (Great Britain Pounds) annually when natural gas replaces diesel fuel. Moreover, CO_2 emission from natural gas is 0.185 kg per kWh [David, J.C. MacKay, 2008]. Less than 10 thousand tonnes of CO_2 is released annually when natural gas replaces diesel fuel to power the oil field. If each of the oil fields in Appendix B demand the same amount of energy, the annual CO_2 emission reduces to about 119,000 tonnes with the use of natural gas. The global offshore energy database now consists of over 9,600 offshore oil fields. Merging this figure with the estimated annual CO_2 emission in Table 5, validates the published 200 million tonnes of CO_2 claimed to manifest annually from offshore oil fields globally.

The analysis so far assumes no storage and zero power from renewables. The simulation result of an improved non-renewable power system in which storage facility is included is summarized in Table 6 (b). This represents the base case system. Comparing the 'a' and 'b' segments of Table 6, the annual fuel consumption is reduced by 11.7% and 11.8% for diesel and natural gas, respectively. These reflect the impact of storage on the power system. The same percentage decrease was observed for the CO_2 emission when diesel and natural gas were considered individually.

Table 6(a): Fuel-Based Scenario

#	Parameter	Fuel Type	
		Diesel	**Natural Gas**
1	Fuel Price (£)	0.27/L	0.10/m^3
2	Energy from Fuel (kWh)	3/L	5.14/m^3
3	Fuel Cost per kWh (£)	0.09	0.02
4	Daily Load Met (kWh)	146,500	146,500
5	CO_2 Emission (kg per unit volume)	2.772/L	0.9509/m^3
6	CO_2 Emission (kg per kWh)	0.924	0.185
7	Daily Fuel Consumption	48,833 L	28,501 m^3
8	Daily Fuel Cost (£)	13,185	2,850
9	Annual Fuel Consumption	17,824,166 L	10,403,210 m^3
10	Annual Fuel Cost (£)	4,812,525	1,040,321
11	Daily CO_2 Emission (kg)	135,366	27,102
12	Annual CO_2 Emission (kg)	49,408,590	9,892,412

Table 6(b): **Base Case System**

#	**Parameter**	**Fuel Type**	
		Diesel	**Natural Gas**
1	Fuel Price (£)	0.27/L	$0.10/m^3$
2	Energy from Fuel (kWh)	3/L	$5.14/m^3$
3	Fuel Cost per kWh (£)	0.09	0.02
4	Daily Load Met (kWh)	146,500	146,500
5	CO_2 Emission (kg per unit volume)	2.772/L	$0.9509/m^3$
6	CO_2 Emission (kg per kWh)	0.924	0.185
7	Daily Fuel Consumption	43,119 L	$25{,}138\ m^3$
8	Daily Fuel Cost (£)	11,642	2,513
9	Annual Fuel Consumption	15,738,435 L	$9{,}175{,}326\ m^3$
10	Annual Fuel Cost (£)	4,249,377	917,537
11	Daily CO_2 Emission (kg)	119,525	23,903
12	Annual CO_2 Emission (kg)	43,626,941	8,724,859

Similarly, it was noticed that natural gas gives only about 20% of emission produced by diesel fuel to generate equivalent power.

Table 7 shows how the input variables were altered for each sensitivity case, while the outcome of each alteration is reflected in Table 8. The optimal system demonstrated its economics relative to the base case system as the annual fuel consumption and the corresponding CO_2 emission decreased by 38% each. The levelized cost of energy also drops from £0.9116 to £0.5276 (42% fall). Power contributions from each of the three sources are as shown in Fig. 4. Annually, a total of 30,033,766 kWh (53.9%) comes from fossil fuel, 16,785,020 kWh (30.1%) from wind power, and 8,943,061 kWh (16.0%) from wave power.

CONCLUSION

It is imperative to reiterate the fact that this study is not intended to argue the economics of renewables against fossil fuel. Rather, it is meant to expose the avoidable harm done to the environment by generating power from fossil fuel to supply offshore oil fields.

Results of this study has shown that the economics of renewable energy is not as bad as thought and there is room for improvement with more use and development of green initiatives. The possibility for more use of renewables is very high if offshore CO_2 tax could be imposed.

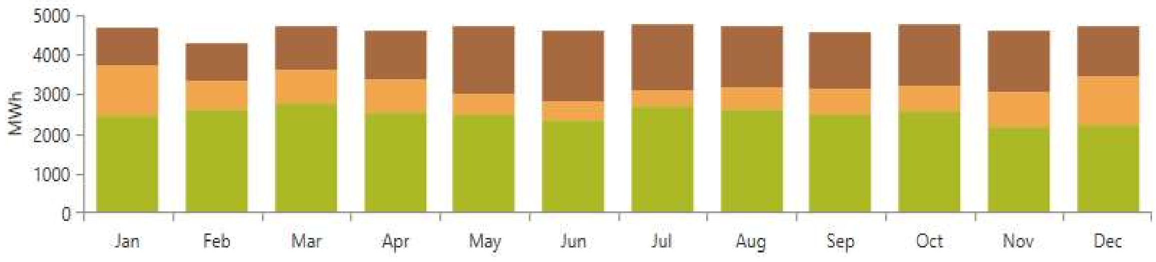

Fig. 4. Monthly Electric Production

Table 7(a): Simulation Parameters

#	Input Variable	Winning System	Sensitivity Case 1	Sensitivity Case 2	Sensitivity Case 3	Sensitivity Case 4	Sensitivity Case 5	Sensitivity Case 6	Sensitivity Case 7
1	**Interest Rate (%)**	8	5	5	5	5	5	5	5
2	**Inflation Rate (%)**	2	2	1	1	1	1	1	1
3	**Annual Capacity Shortage (%)**	0	0	0	5	5	5	5	5
4	**Project Lifetime (Years)**	25	25	25	25	30	30	30	30
5	**Hub Height (m)**	73	73	73	73	73	100	100	100
6	**Diesel Gen. Lifetime (hours)**	15,000	15,000	15,000	15,000	15,000	15,000	30,000	30,000
7	**Turbine Lifetime (years)**	20	20	20	20	20	20	20	30
8	**WEC Lifetime (years)**	15	15	15	15	15	15	15	15
9	**TLC Lifetime (years)**	20	20	20	20	20	20	20	20
10	**Diesel Fuel Price (£/L)**	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
11	**NG Gen. Lifetime (hours)**	–	–	–	–	–	–	–	–
12	**NG Price (£/m^3)**	–	–	–	–	–	–	–	–
13	**CHP Heat Recovery Ratio (%)**	–	–	–	–	–	–	–	–

Table 7(b): Simulation Parameters (Continued)

#	Input Variable	Sensitivity Case 8	Sensitivity Case 9	Sensitivity Case 10	Sensitivity Case 11	Sensitivity Case 12	Sensitivity Case 13	Sensitivity Case 14	Sensitivity Case 15
1	**Interest Rate (%)**	5	5	5	5	5	5	5	5
2	**Inflation Rate (%)**	1	1	1	1	1	1	1	1
3	**Annual Capacity Shortage (%)**	5	5	5	5	5	5	5	5
4	**Project Lifetime (Years)**	30	30	30	30	30	30	30	30
5	**Hub Height (m)**	100	100	100	100	100	100	100	100
6	**Diesel Gen. Lifetime (hours)**	30,000	30,000	30,000	30,000	–	–	–	–
7	**Turbine Lifetime (years)**	30	30	30	30	30	30	30	30
8	**WEC Lifetime (years)**	20	20	20	20	20	20	20	20
9	**TLC Lifetime (years)**	20	30	30	30	30	30	30	30
10	**Diesel Fuel Price (£/L)**	0.27	0.27	0.351	0.189	–	–	–	–
11	**NG Gen. Lifetime (hours)**	–	–	–	–	50,000	50,000	50,000	80,000
12	**NG Price $(\pounds/m^3)$**	–	–	–	–	0.351	0.64	0.12	0.351
13	**CHP Heat Recovery Ratio (%)**	–	–	–	–	20	20	20	20

Table 8: Simulation Results

#	Parameter	Base Case System	Winning System	Sensitivity Case 1	Sensitivity Case 2	Sensitivity Case 3	Sensitivity Case 4
1	**Renewable Fraction (%)**	0	21.1	21.1	21.1	31.2	31.2
2	**Fuel Used (Litres/year)**	15,738,435	12,417,625	12,417,625	12,417,625	12,355,536	12,355,536
3	**Fuel Cost ($£/year$)**	4,249,377	3,352,758	3,352,758	3,352,758	3,335,994	3,335,994
4	**CO$_2$ Emission (kg/year)**	43,626,941	34,421,656	34,421,656	34,421,656	34,249,548	34,249,548
5	**LCOE ($£/kWh$)**	0.9116	0.7193	0.6114	0.6420	0.6337	0.6104
6	**Net Present Cost (£)**	2,156,448,865	2,085,591,260	2,419,285,861	2,274,128,709	2,245,929,513	2,384,727,956
7	**Initial Capital (£)**	1,306,379,890	1,959,569,835	1,959,569,835	1,959,569,835	1,935,859,039	1,935,859,039
8	**O&M ($£/year$)**	82,748,290	53,786,388	73,149,487	65,468,790	64,329,633	70,576,040
9	**Salvage Value (£)**	-63,831,790	-102,130,864	-206,304,345	-161,329,997	-174,994,647	-268,616,783
10	**ROI (%)**	22.6	37.6	37.6	37.6	40.1	40.2
11	**IRR (%)**	20.7	16.3	16.3	16.3	17.4	17.4
12	**Simple Payback (Years)**	5.1	8.5	8.5	8.5	8.3	8.3

#	Parameter	Sensitivity Case 5	Sensitivity Case 6	Sensitivity Case 7	Sensitivity Case 8	Sensitivity Case 9	Sensitivity Case 10
1	**Renewable Fraction (%)**	31.6	31.6	31.6	31.6	31.6	31.6
2	**Fuel Used (Litres/year)**	12,194,914	12,194,914	12,194,914	12,194,914	12,194,914	12,194,914
3	**Fuel Cost ($£/year$)**	3,292,626	3,292,626	3,292,626	3,292,626	3,292,626	4,280,414
4	**CO$_2$ Emission (kg/year)**	33,804,301	33,804,301	33,804,301	33,804,301	33,804,301	33,804,301
5	**LCOE ($£/kWh$)**	0.6054	0.4803	0.4803	0.4803	0.4803	0.4820
6	**Net Present Cost (£)**	2,370,658,061	1,879,694,776	1,878,877,108	1,878,839,530	1,878,837,401	1,887,292,169
7	**Initial Capital (£)**	1,935,859,039	1,935,859,039	1,935,859,039	1,935,859,039	1,935,859,039	1,935,859,039
8	**O&M ($£/year$)**	69,693,839	69,693,839	69,693,839	69,693,839	69,693,839	69,693,839
9	**Salvage Value (£)**	-269,046,569	-300,363,589	-298,140,898	-298,251,210	-298,245,244	-298,245,244
10	**ROI (%)**	40.5	20.7	20.8	20.8	20.8	21.1
11	**IRR (%)**	17.3	8.5	8.5	8.5	8.5	8.6
12	**Simple Payback (Years)**	8.4	13.1	13.1	13.1	13.1	13.1

#	Parameter	Sensitivity Case 11	Sensitivity Case 12	Sensitivity Case 13	Sensitivity Case 14	Sensitivity Case 15	Optimal System
1	**Renewable Fraction (%)**	31.6	31.6	31.6	31.6	31.6	37.7
2	**Fuel Used (Litres/year)**	12,194,914	7,109,634	7,109,634	7,109,634	7,109,634	6,430,067
3	**Fuel Cost ($£/year$)**	2,304,838	2,495,481	4,550,165	853,156	2,495,481	2,256,953
4	**CO$_2$ Emission (kg/year)**	33,804,301	6,760,550	6,760,550	6,760,550	6,760,550	6,114,350
5	**LCOE ($£/kWh$)**	0.4787	0.5909	0.6425	0.4547	0.4086	0.5276
6	**Net Present Cost (£)**	1,887,290,470	2,264,748,564	2,604,460,848	1,925,036,279	1,347,525,395	1,368,056,200
7	**Initial Capital (£)**	1,935,859,039	2,323,030,846	2,323,030,846	2,323,030,846	2,323,030,846	1,371,698,884
8	**O&M ($£/year$)**	69,693,839	83,632,606	96,177,496	71,087,715	92,414,029	46,339,042
9	**Salvage Value (£)**	-298,245,244	-357,894,292	-357,894,292	-357,894,292	143,157,716	-91,917,777
10	**ROI (%)**	20.5	24.6	20.9	28.3	45.3	62.8
11	**IRR (%)**	8.4	10.1	8.6	11.6	18.6	11.7
12	**Simple Payback (Years)**	13.1	15.7	18.1	13.3	9.3	15.2

Making oil industries responsible for the detrimental effects of burning fossil fuel is vital to attaining the net zero carbon target. The imposition of carbon tax should be globally embraced because many countries expand their economy as they increase their CO_2 emissions, while others are making effort to reduce GHG emissions at the expense of their own economic growth. Enforcement of CO_2 tax can also discourage gas flaring which has been a common practice due to inadequate pipelines and gas treating facilities. Globally, offshore oil fields consume about 16 TeraWatt-hour annually. Meeting this demand exclusively via renewables is not feasible at the moment. Hybrid power system with more penetration of renewables is therefore suggested as a solution. The proposed model is anchored on enthusiasm that a breakthrough is expected very soon on wave energy converters with ongoing research on suitable control strategy to pilot movement of the machine relative to the waves acting on it to attain resonance for maximum power extraction. Executing this project as a case study of a particular offshore oil field with real-life data is recommended for more specific results.

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APPENDIX A – Selected Wind Farms in the UK North Sea

#	Name	Distance to Shore (km)	Depth Range (m)	Capacity (MW)	Installed Turbines	Build Cost (£) (Million)	Date Built
1	**Blyth Offshore**	**1.6**	6-11	**4**	**2 x Vestas V66-2MW**	**4**	**2000**
2	**Scroby Sands**	**2.5**	0-8	**60**	**30 × Vestas V80-2MW**	**75.5**	**2004**
3	**Kentish Flats**	**10**	3-5	**90**	**30 × Vestas V90-3.0MW**	**121.5**	**2005**
4	**Beatrice**	**13**	45	**10**	**2 × REpower 5MW**	**35**	**2007**
5	**Lynn & Inner Dowsing**	**5**	6-11	**194**	**54 × Siemens SWP-3.6-107**	**300**	**2009**
6	**Thanet**	**11**	20-25	**300**	**100 × Vestas V90-3.0MW**	**900**	**2010**
7	**Gunfleet Sands 1 & 2**	**7**	2-15	**172**	**48 × Siemens SWP-3.6-107**	**300**	**2010**
8	**Greater Gabbard**	23	20-32	**504**	**140 × Siemens SWT-3.6-107**	**1,500**	**2012**
9	**Sheringham Shoal**	**17**	12-24	**317**	**88 × Siemens SWT-3.6-107**	**1,100**	**2012**
10	**London Array**	**20**	0-25	**630**	**175 × Siemens SWT-3.**	**1,800**	**2013**
11	**Lincs**	**8**	10-15	**270**	**75 x Siemens SWT-3.6-120**	**1000**	**2013**
12	**Teesside**	**1.5**	7-15	**62**	**27 x Siemens SWT-2.3**	**200**	**2013**
13	**Humber Gateway**	**10**	15	**219**	**73 × Vestas V112-3.0**	**900**	**2015**
14	**Westermost Rough**	**8**	15	**210**	**35 x Siemens SWT-6.0**	**1000**	**2015**
15	**Dudgeon**	**32**		**402**	**67 × Siemens SWT-6.0-154**	**1.5**	**2017**
16	**Beatrice**	**13**	45	**588**	**87 × 7MW Siemens GamesaRE**	**2,600**	**2019**

https://mangomap.com/engineering/maps/74202/north-sea-wind-farms#

APPENDIX B – Selected Oil Fields in the UK North Sea

#	Oil Field	Approximate Distance From Shore	~ Water Depth (m)	Operator	Partners
1	Buzzard	100km north-east of Aberdeen (Central North Sea)	100	Nexen Petroleum UK, (43.21%)	Suncor UK (29.89%) BG Group (21.73%) Edinburgh Oil and Gas (5.16%)
2	Captain	145km north-east of Aberdeen	105.5	Chevron (85%)	Korea Captain Company Hanwha Energy
3	Forties	177km east of Aberdeen	106	From BP to Apache	
4	Alba	210km north-east of Aberdeen	138	Chevron (23.37%)	Endeavour (25.68%) Statoil (17%) Mitsui (13.3%) Total (12.65%) EnQuest (8%)
5	Machar	240km east of Aberdeen (Central North Sea)	95	BP	
6	Harding	322km north-east of Aberdeen (Central North Sea)	110	From BP to Abu Dhabi National Energy Company (70%)	Maersk Oil
7	Clair	75km west of the Shetland Islands	140	BP (28.6%)	Shell (27.9%) ConocoPhillips (24%) Chevron (19.4%)
8	Ninian	144km east-northeast of Shetland Island (Northern North Sea)	141	CNR: Canadian Natural Resources (87.06%)	Eni UK
9	Don Southwest	150km north-east of the Shetland Islands (Northern North Sea)	170	EnQuest (60%)	Ithaca Energy (40%)
10	Schiehallion	175km west of Shetland	350 to 450	BP (33.35%)	Shell (54.9%) OMV (11.75%)
11	Foinaven	190km west of the Shetland Islands	400 to 600	BP (70%)	Marathon (30%)
12	Statfjord	Extends across the UK-Norwegian boundary, with 85.47% lying in Norway and the remaining in the UK.	145	Statoil (44.3%)	ExxonMobil (21.4%) Centrica Resources (14.5%) Centrica Resources Norge (19.8%)

https://www.offshore-technology.com/features/featuredeep-pockets-the-biggest-offshore-oil-fields-in-the-uk-north-sea-

APPENDIX C – Manufacturer's Diesel Fuel Estimation

Gen. Size (kW)	**Approximate Natural Gas Consumption (Cubic Meter per Hour)**			
	$\frac{1}{4}\boldsymbol{F_L}$	$\frac{1}{2}\boldsymbol{F_L}$	$\frac{3}{4}\boldsymbol{F_L}$	$\boldsymbol{F_L}$
20	4.45	5.32	6.99	8.18
30	5.72	7.36	9.85	11.78
40	6.97	9.43	12.71	15.38
60	9.46	13.56	18.46	22.34
75	11.33	16.65	22.74	28.03
100	14.44	21.83	29.90	37.04
125	17.58	26.99	37.04	46.07
135	18.83	29.05	39.90	49.67
150	20.70	32.14	44.20	55.10
175	23.81	37.29	51.34	64.11
200	26.96	42.48	58.50	73.14
230	30.70	48.65	67.08	83.96
250	33.19	52.78	72.80	91.18
300	39.45	63.12	87.10	109.22
350	45.70	73.43	101.40	127.28
400	51.93	83.76	115.70	145.32
500	64.45	104.40	144.30	181.43
600	76.94	125.05	172.93	217.50
750	95.68	156.00	215.83	271.64
1000	126.92	207.62	287.33	361.89

https://www.generatorsource.com/temp/Fuel_Consumption_Chart.pdf

APPENDIX D – Manufacturer's Natural Gas Estimation

Gen. Size (kW)	**Approximate Natural Gas Consumption (Cubic Meter per Hour)**			
	$\frac{1}{4}\boldsymbol{F_L}$	$\frac{1}{2}\boldsymbol{F_L}$	$\frac{3}{4}\boldsymbol{F_L}$	$\boldsymbol{F_L}$
20	4.45	5.32	6.99	8.18
30	5.72	7.36	9.85	11.78
40	6.97	9.43	12.71	15.38
60	9.46	13.56	18.46	22.34
75	11.33	16.65	22.74	28.03
100	14.44	21.83	29.90	37.04
125	17.58	26.99	37.04	46.07
135	18.83	29.05	39.90	49.67
150	20.70	32.14	44.20	55.10
175	23.81	37.29	51.34	64.11
200	26.96	42.48	58.50	73.14
230	30.70	48.65	67.08	83.96
250	33.19	52.78	72.80	91.18
300	39.45	63.12	87.10	109.22
350	45.70	73.43	101.40	127.28
400	51.93	83.76	115.70	145.32
500	64.45	104.40	144.30	181.43
600	76.94	125.05	172.93	217.50
750	95.68	156.00	215.83	271.64
1000	126.92	207.62	287.33	361.89

https://www.generatorsource.com/temp/Fuel_Consumption_Chart.pdf