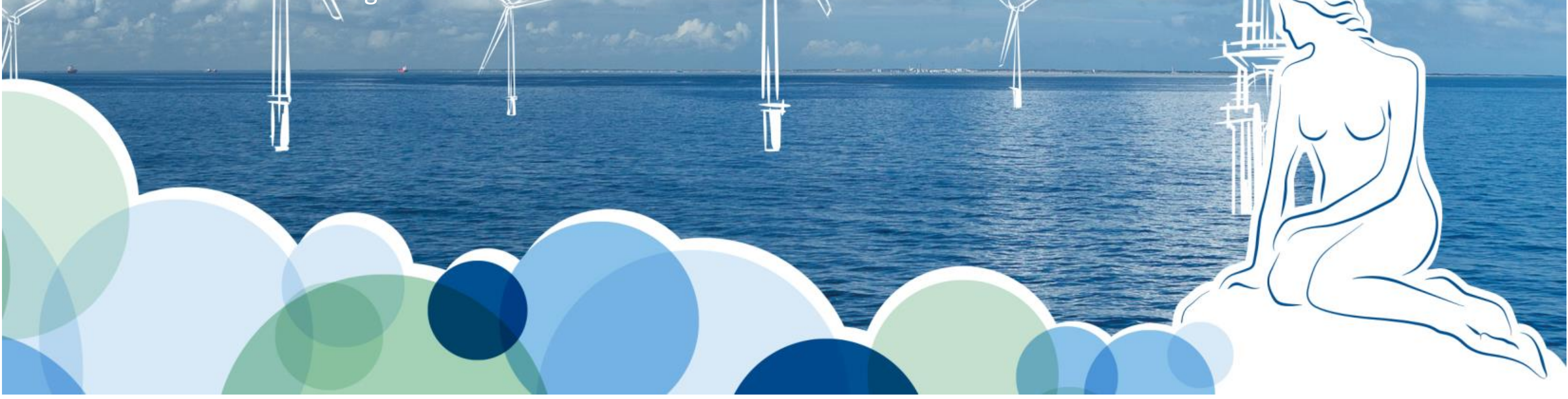
Resource Assessment for Offshore Green Hydrogen Production

Hydrogen is a low carbon energy carrier with the ability to reduce emissions from a variety of sectors such as heating, transportation, heavy industry and power generation. With renewable energy expanding further offshore, there is potential to repurpose existing oil and gas infrastructure for transporting energy to land in the form of molecules, such as hydrogen, rather than building expensive new cables to connect wind farms to an already constrained grid. Hydrogen can help to balance intermittent renewable energy supply as well as store the excess power that would otherwise be curtailed. Areas around Scotland have been determined, which match offshore renewable and oil and gas areas of interest that could be used to produce green hydrogen offshore. A resource assessment was carried out on one of the identified sites to estimate approximate annual energy yield available for hydrogen production. The average annual energy yield (P50) was 5576.3 GWh/year with the capacity factor for the 'grid-less' wind farm of 42.4%. Four different scenarios were used in order to analyse the impact of the availability of the electrolyser on the capacity factor for 'grid-less' wind farms. Capacity factor can vary up to 4.1%, which translates to 27.7 tons of hydrogen lost per day. This could power up to 155 trains, 2,770 buses or provide a full tank for up to 5,540 cars contributing towards the 2045 net zero carbon target in Scotland.



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1.1. INTRODUCTION

To meet the 2045 net zero carbon targets in Scotland, more renewable energy converters are installed every year. This increases the amount of curtailed energy and subsequently results in constraint payments reaching over £118 million in 2019 UK wide [1]. While renewables are decarbonising the power grid, the carbon emissions in other sectors like industry and transportation have increased [2].

With renewable energy expanding further offshore, there is potential to repurpose existing oil and gas (O&G) infrastructure for transporting the energy to land in the form of molecules, such as hydrogen, rather than building new cables to connect wind farms to an already constrained grid [3] [4]. According to a study conducted by TU Delft, for similar investment, a pipeline can transport between ten and twenty times more energy than cable [5].

Hydrogen can achieve near zero-carbon footprint when produced from renewable feedstocks [6]. This allows for decarbonisation of the afore mentioned sectors and where existing infrastructure is repurposed, potentially deferring a significant proportion of the estimated £15.3 billion cost to be spent on decommissioning in the UK continental shelf by 2027 [7]. The current total cost of decommissioning the remaining UK offshore O&G production, transportation and processing infrastructure is estimated at £51bn [8]. Producing hydrogen offshore is also often perceived safer than producing it onshore, resulting in higher public acceptance and support [3].

This research first determines areas around Scotland that match sources of offshore renewable energy (ORE) with the location of O&G infrastructure and therefore have the potential to produce green hydrogen. One of these identified areas has been chosen for further resource assessment analysis to determine the estimated energy yield of the site. The area of search chosen is the N8 area located approximately 100km from the Shetland islands. The distance from land and the constrained grid situation on the islands makes the windfarm connection with land via cable rather questionable. On the other hand, the close proximity of three O&G platforms and three possible pipeline routes makes the area ideal for further consideration for converting the wind energy into molecules instead. This paper presents the energy yield and design of the offshore windfarm at the area N8 and further investigates the variability of the capacity factor (CF) of the wind farm, with the availability of the electrolyser in the case where the wind farm is not grid connected with the onshore network. This research demonstrates the importance of an integrated approach to design of the hydrogen plant and the windfarm and is a part of the author's EngD research on techno-economic feasibility of offshore hydrogen production.

1.2. METHODOLOGY

1.2.1. MAPPING

Offshore O&G and renewable energy areas have been mapped using the Quantum Geographic Information System (QGIS 2.18) [9]. In order to make an overall map of offshore O&G infrastructure and planned and existing offshore renewable sites such as the one in Figure 1, different shapefiles from Marine Scotland and Oil and gas authority (OGA) were updated using information from the Offshore petroleum regulator for environment and decommissioning (OPRED). Four areas have been identified as potential sites for offshore hydrogen production due to the presence of both O&G infrastructure and ORE. Three of these areas contain offshore wind areas of search (AoS) based on the 2018 scientific study conducted by Marine Scotland Science [10]. AoS are sites recommended by Marine Scotland to offshore wind developers as a result of weighting 20 relevant GIS layers looking into potential areas of opportunity and constraint. These layers featured the following aspects: bathymetry, wind resource, fishing, aviation, defence, shipping, protected areas, cultural heritage, social considerations, future trends, supply chains and O&G installations. These sites should have appropriate resource and face the least obstructions during consenting and licensing [10][11].

1.2.2. RESOURCE ASSESMENT AND ANNUAL ENERGY YIELD ANALYSIS

The wind resource assessment was conducted based on the ERA-5 reanalysis long term dataset. This data set has been chosen as a compromise between data availability and resolution. A Vestas V164 10MW turbine model was considered with a hub height of 105 m AMSL. All sites identified (except Beatrice) are in water depth greater than 60 m, implying the use of floating offshore wind turbines. Many new planned floating wind projects are coming close to 10 MW. For example Equinor is aiming to install an 8 MW turbines for their Hywind Tampen project [12], Vestas will install five of their V164-9.5MW turbines in spring 2020 for the Kincardine floating wind farm [13] and Principle Power and Senvion are planning to float a 10-MW turbine through a European Commission funded project [14]. The windfarm layout was designed based on the latest leasing round specifications from the Crown Estate with spacing between the wind turbines of 12 diameters in the prevailing wind direction and 8 diameters in the non-prevailing wind direction with a staggered configuration in WindPRO v 3.0 [15]. This assumed spacing resulted in wake loss of 7.38%.

The annual energy yield prediction was calculated using a linear flow model in WAsP 11 that enables horizontal and vertical extrapolation of wind statistics in order to predict wind climate, wind resource and energy yield from individual wind turbines or entire wind farms. By providing WAsP with a power curve, it was possible to calculate the actual, annual mean energy production of the wind farm by combining it with the total energy content of the mean wind modelled in WindPro v3.0. With the addition of the thrust coefficient curve and the windfarm layout, wake loss of each turbine was estimated and thus the net annual energy production could be calculated [16]. As the information needed for the annual energy yield prediction such as the power and thrust curves are confidential, the curves from the 10 MW reference wind turbine from the Technical University of Denmark were used [5]. The power curve was scaled from 10.6 MW to 10 MW.

A combined uncertainty was calculated using square root of sum of the squares of the series of different losses resulting from uncertainty in site measurement, historic wind resource, extrapolation, future wind variability, spatial variation and plant performance.

1.2.3. CAPACITY FACTOR (CF)

CF is a ratio between actual energy output of a windfarm and maximum theoretical energy output of the windfarm. Windfarms do not produce at full capacity due to several effects and losses such as wind variability, wake loss, electrical transmission, wind hysteresis etc. In this study, the effect of the availability of the electrolyser on the CF is investigated by changing the number of hours the electrolyser is available in comparison to the wind turbine generators (WTGs). For the purpose of this study, the WTG downtime is fixed at 6% based on the Crown Estate report [17].

In order to see the rate of change of the CF based on the electrolyser availability, different scenarios with varying electrolyser availability were considered and are presented in Table 1. The most conservative scenario, Scenario 4, includes the instance where the electrolyser operates 8000 hours (91.3%) a year as in a typical chemical plant [18] and the maintenance is not coordinated with WTG maintenance. This is indicated in Table 1 by 0% for combined maintenance and by 14.7% for the total maintenance. In the most optimistic scenario, Scenario 1, the WTG maintenance takes place at the same time as the electrolyser's maintenance (coordinated approach) and the electrolyser is down for 6% of the time or less, similar to the WTG. The electrolyser availability represents the percentage relative to when the windfarm is operating rather than the total availability i.e. in Scenario 1 the electrolyser is 100% available when the windfarm is operating but there is maintenance taking place on the electrolyser during the WTG maintenance thereby resulting in total electrolyser availability of 94% above. The two scenarios between the two extremes have been calculated by incorporating the hourly windspeed data for the site for past 21 years. Ideally, the electrolyser's maintenance should be taking place during the time when the wind turbines are not operating in order to minimise energy loss. This happens during WTG maintenance but also when the windspeed is below cut-in speed or over cut-off speed. Occurrences, when the windspeed is higher than cut-off were not considered as these are not suitable for maintenance. However, the windspeeds below cut-in speed will be ideal for the maintenance. The occurrences of windspeeds below 3 m/s used were during daylight between the months of April and September. The total hours calculated were 251.1 hours or 2.9% hours per year. Scenario 2 shows the electrolyser requiring 8.7% of maintenance time (operating 8000 hours) where 6% is done simultaneously with the WTG and 2.7% is done separately. Scenario 3 describes partially coordinated maintenance between the WTG and electrolyser where 2.9% of hours with windspeed below cut-in speed are used for maintenance of both and the rest of the maintenance is done separately for WTG and electrolyser throughout the year (with electrolyser operating 8000 hours). The results are presented in Table 5 of the Results section.

Table 1 The summary of the different scenarios.

Scenario	Wind Farm Availability %	Electrolyser Availability * %	Combined Maintenance %	Total Maintenance %
1	94	100	6	6
2	94	97.3	6	8.7
3	94	94.2	2.9	11.8
4	94	91.3	0	14.7

*when the windfarm is operating

1.3. RESULTS

1.3.1. MAPPING

Figure 1 shows the result of combining several different GIS layers in UKCS around Scotland. There are four areas encircled that show potential or existing offshore wind infrastructure near existing O&G assets. Area A is north of Shetlands, area B is north east of St Fergus with 3 wind AoS, area C is east of Aberdeen and D is in Moray Firth. The O&G infrastructure count for the four areas is presented in Tables 2 and 3 with more detailed maps of the areas and named O&G platforms in Figure 2.

Figure 1 Map of offshore renewable and O&G areas of interest around Scotland.

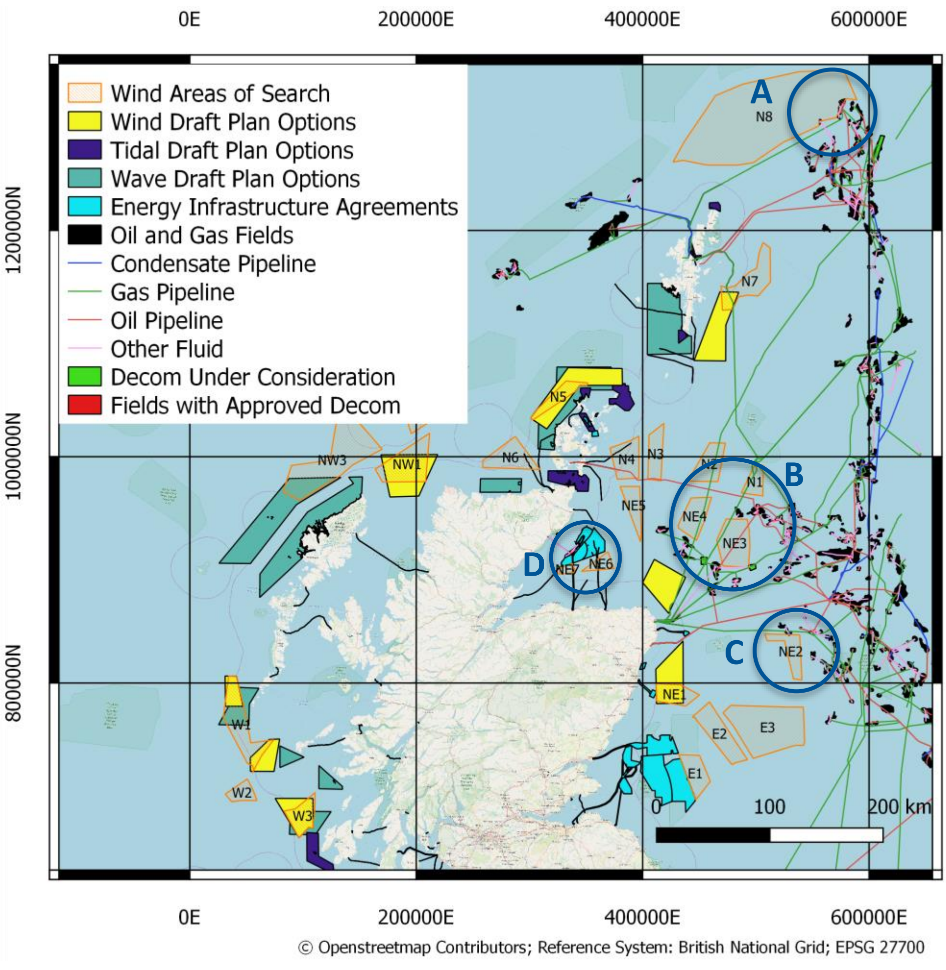


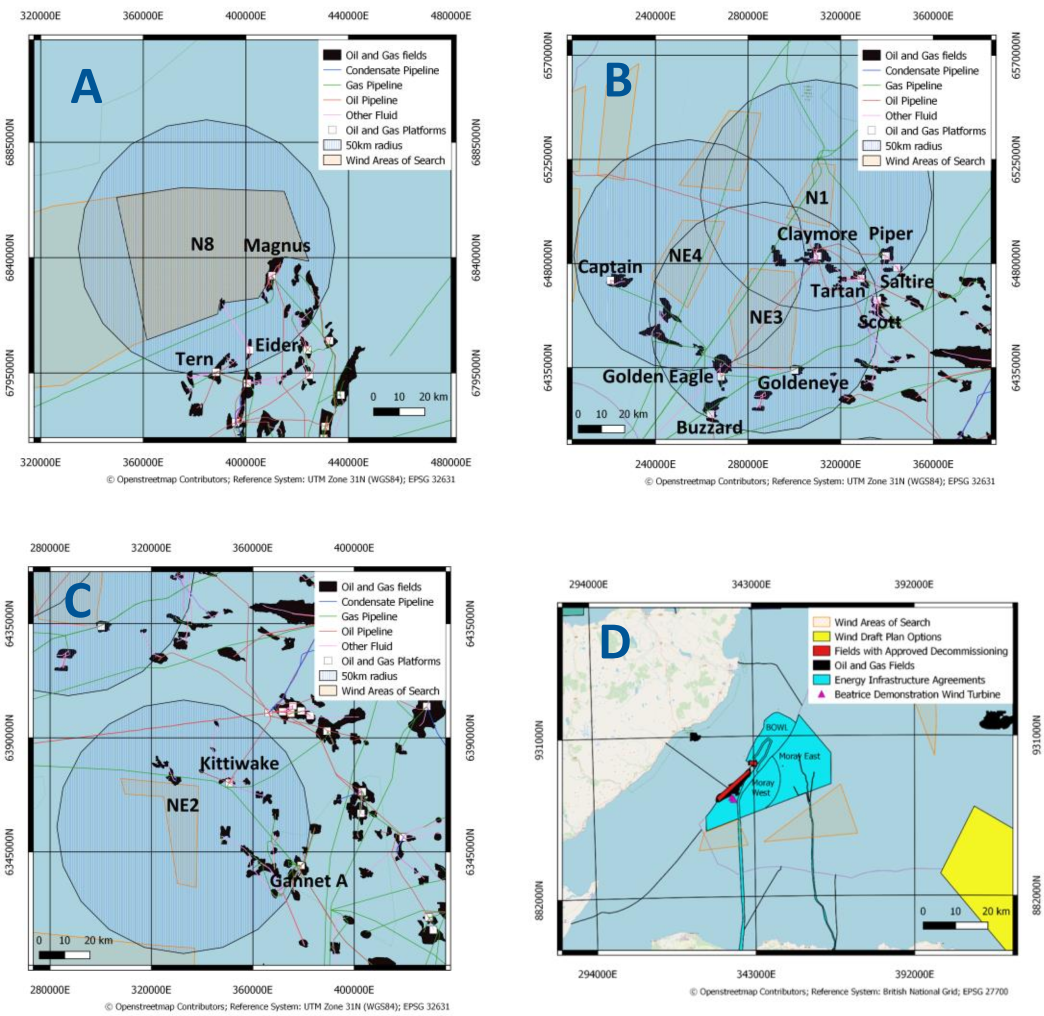
Table 2 Areas of interest identified for potential offshore hydrogen production with the O&G infrastructure count.

	A	B			C
Wind AoS	N8	NE3	NE4	N1	NE2
O&G platforms within 50km radius	3	6	1	4	2
O&G pipelines from platforms	3	10	1	4	4

Table 3 Moray Firth area identified for potential offshore hydrogen production with the O&G and ORE infrastructure count.

	D
Offshore Wind Developments	4
O&G platforms	2
O&G pipelines	1

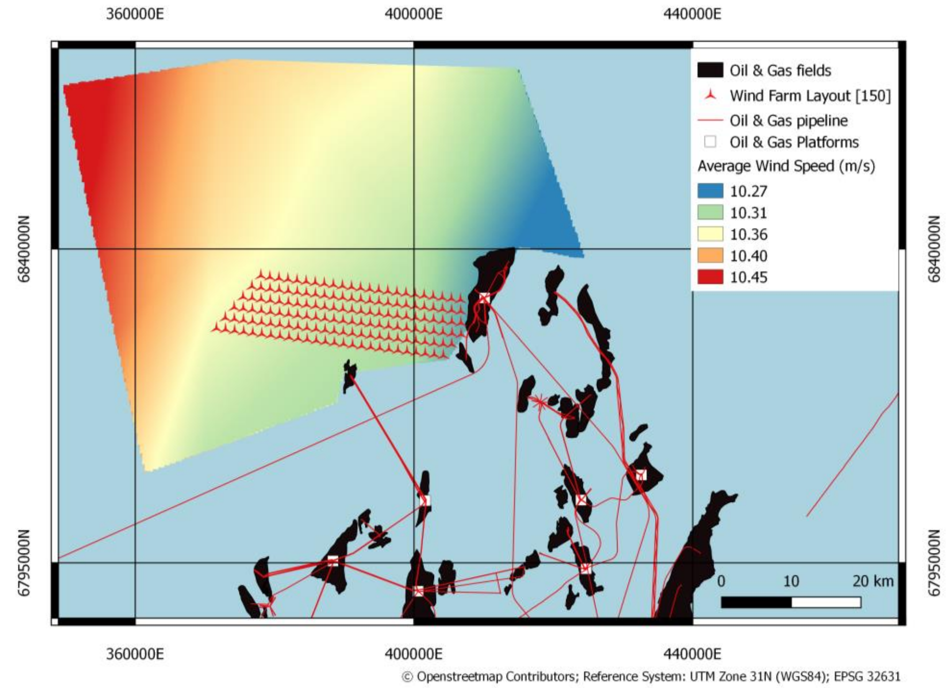
Figure 2 Close up maps of identified areas for offshore hydrogen production around Scotland showing oil and gas infrastructure within 50km radius from wind AoS.



1.3.2. ENERGY YIELD

A resource assessment and a hypothetical offshore windfarm energy yield analysis has been carried out on area A. The horizontally interpolated wind resource of scaled AoS N8 can be seen in Figure 3. As the full area covers 7937 km^2, it was scaled down to 3000km^2 according to previous implication of Crown Estate Scotland to cap the maximum area of an

Figure 3 Scaled N8 area wind resource and the chosen layout for the 1.5 GW windfarm with staggered configuration.



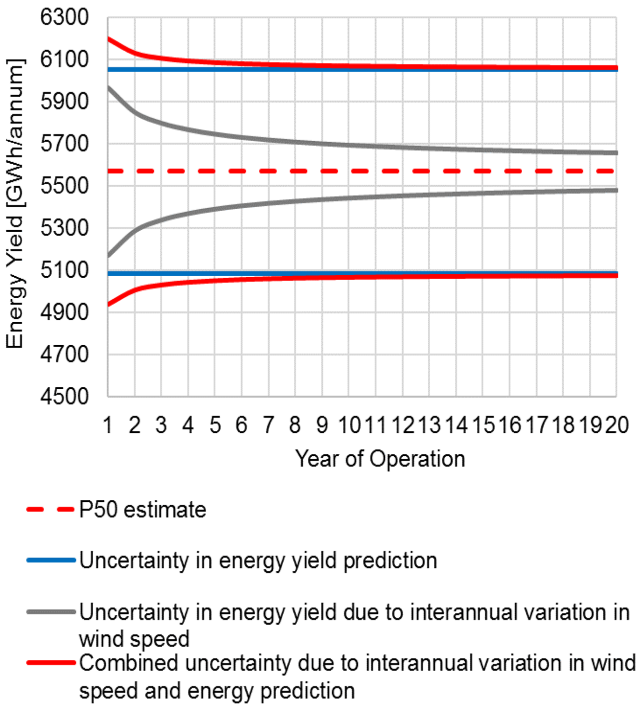
individual application to 'thousands of km^2' as well as limiting the seabed to one draft plan area per application.[19]The upper limit of 3,000 km^2 has been previously under consideration, however Crown Estate Scotland 'does not intend to impose a cap on the total amount of seabed awarded per round of leasing'. [20] As the newest draft plan options are still being designed by Marine Scotland, limiting the area to 3,000 km^2 was considered reasonable. As the scaled area can fit 1,366 Vestas V-164 turbines resulting in 13.66 GW capacity, the windfarm layout was designed based on the latest leasing rounds specifications from The Crown Estate taking an upper limitation of 1.5 GW per wind farm [21], which is shown in Figure 3.

Table 4 summarises the wind farm energy yield calculated for the 1.5 GW wind farm using WaSP. The gross windfarm energy production was calculated to be 7607 GWh/year. Applying losses caused by effects such as wake loss, electrolyser availability, wind turbine availability, blade contamination, wind interannual variability, wind hysteresis, losses due to instrumentation and control, etc the average annual energy yield predicted (P50) comes down to 5576.3 GWh/year. Graphic representation of the uncertainties in the N8 windfarm energy yield prediction at the proposed hub height for the WTG type considered are shown in Figure 4. The red dashed lines show the predicted P50 yield for the Project. The blue lines represent the P10 / P90 uncertainty in the measurements and the energy yield prediction methodology; this uncertainty remains constant through the lifetime of the Project. The red solid lines represent the total uncertainty in energy yield when interannual variability is combined with the uncertainty in the yield prediction. This total uncertainty decreases over the lifetime of the Project. The lower limit on the graph corresponds to the P90 and the upper limit corresponds to the P10.

Table 4 The summary of the P50 energy yield results.

Overall Conversion Efficiency [%]	73.3
Wind Farm Energy Yield [GWh/yr]	5576.3
Capacity Factor [%]	42.4
Standard Error in Energy Yield [%]	6.8
Standard Error in Energy Yield [GWh/yr]	378.7

Figure 4 The uncertainty of the energy yield changing with the number of years of the windfarm in operation.



1.3.3. CAPACITY FACTOR

The results of the four different scenarios (explained in the section 1.2.3 of Methodology) showing the change of CF based on the electrolyser availability are presented in Table 5. CF varies as much as 4.1% between different scenarios for wind farms that are not connected to the grid.

Table 5 The summary of the different scenarios showing change in the P50 capacity factor.

Scenario	1	2	3	4
CF %	46.5	45.2	43.7	42.4

1.4. DISCUSSION

1.4.1. MAPPING

None of the draft plan options for tidal and wave developments were located in proximity of O&G infrastructure and thus this paper concentrates on the wind technology only. Currently wind turbines are more mature than wave and tidal, being able to harvest more energy and thus being more suitable for bulk hydrogen production. However, it may be worth considering wave and tidal technology in the future for smaller scale projects.

Four areas have been identified as being suitable for offshore hydrogen production in UKCS around Scotland. Three of these areas are located in deep waters near areas of potential future floating wind developments. One area, Moray Firth, is in shallow water with an existing grid connection to one of the platforms and existing and planned wind farms. If there was to be a pilot project for offshore hydrogen production in Scotland, the Beatrice platform would have been suitable as it was first platform in Scotland to be electrified and connected to two 5MW wind turbines as well as the grid. The Beatrice platform already ceased production in 2015 and the decommissioning programme was published in December 2018. The removal of the Beatrice facilities is scheduled from 2024 to 2029 [22]. The majority of the platforms in the areas A, B and C are estimated to cease production by 2026 according to the Rystad database [23]. With the current legislation, the infrastructure needs to be removed once abandoned [24]. Keeping the assets available after abandonment is expensive, thus it is of crucial importance to consider offshore hydrogen production and initiate pilot projects now, before the O&G infrastructure is removed from the seabed.

1.4.2. ENERGY YIELD AND CAPACITY FACTOR

The calculated capacity factor for the model windfarm connected to the electrolyser in area A is 42.4%, which is over 5% more than the average European offshore wind capacity factor [25]. One key finding of this study is that CF can be further optimised if the electrolyser's maintenance is coordinated with the maintenance of the windfarm. Scenario 1 results in the same value of capacity factor as in the case of grid connected windfarm without curtailment or with several electrolyser units with alternating down time. Some literature suggests electrolyser availability over 98% [26], which if coordinated with windfarm maintenance would result in 46.5% CF, which is the same as in Scenario 1. This number however does not represent the harsh offshore environment and potential limitation with accessibility of the site, which might decrease the availability of the electrolyser. Other studies quote availability of the electrolyser of 8,000 hours, which is typical for the majority of chemical plants and thus have been used in different ways in the rest of the Scenarios [18].

Taking the lower heating value for hydrogen and 60% efficiency of the electrolyser [27], the 4.1% difference between CF in Scenario 1 and 4 represents hydrogen that could supply up to 2,770 buses covering 100km/day (based on Aberdeen model of hydrogen buses [28]) and 5,540 full tanks for personal cars a day (based on Toyota Mirai car model [29]). As a measure of significance, there are over 700 buses operating in Edinburgh alone [30], therefore even a percentage as low as 4.1% can make a big difference in decarbonisation efforts of any country. Thus, it is essential to design the windfarm together with the electrolyser in order to minimise the loses due to electrolyser's unavailability.

1.5. CONCLUSION

This research maps possible sites for offshore hydrogen production in Scotland. There were 4 areas identified where existing O&G infrastructure coincides with already existing or potential offshore wind sites. The majority of the sites are in deep water indicating the use of floating wind technology for production of offshore hydrogen on O&G infrastructure. In order to utilise the O&G infrastructure for hydrogen production, it is important to act now, before suitable sites are decommissioned. The results presented show the importance of integrating the design of the hydrogen plant with the windfarm at an early stage in order to optimise the performance of both as the availability of the electrolyser can have significant impact on CF when no grid is available.

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