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A Review of Renewable Electricity Cost and Capacity Factor Impact on Green Hydrogen Levelized Cost in Off-grid Configuration

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Abstract

Green hydrogen development is still at a niche stage and faces several technical & commercial barriers. Among them is the high LCOH (Levelized Cost of Hydrogen) of green hydrogen, predominantly due to the cost of renewable electricity. In recent years, several research studies have focused on finding the most cost-effective renewable electricity option to feed electrolyzers for producing green hydrogen. However, their findings suggest that renewable electricity costs vary widely between solar, onshore wind, and offshore wind technologies based on the meteorological conditions of the location. With a focus on the United Kingdom (UK), this paper does a high-level business case analysis to assess renewable electricity options considering their impact on the green hydrogen LCOH in off-grid configuration. The paper uses the cost and capacity factors of renewable electricity generated from solar, onshore wind, and offshore wind in the UK. The paper discusses how offshore wind electricity in an off-grid configuration could be the most effective in bringing down the green hydrogen LCOH and reducing offshore wind curtailments in the UK.

Keywords: business case, green hydrogen, renewable electricity, capacity factor, electrolyzer

1. Introduction

1.1 Background

Green hydrogen production units must be fed with a renewable electricity supply; the availability and cost of renewable electricity are location-dependent and vary significantly with meteorological conditions. Renewable electricity is the most significant cost factor in the green hydrogen LCOH (IRENA, 2020). The feasibility of setting up large-scale green hydrogen production units depends on the availability of low-cost renewable electricity sources (Cammeraat et al., 2022). Hence, green hydrogen producers must explore locations having high volume and low cost of renewable electricity (solar or wind) for setting up green hydrogen plants (IERNA,2020). North Africa, the Mediterranean region, the Middle Eastern, and Southeast Asian countries have high solar energy potential. In contrast, the Nordic region, North America, and West European countries have high wind energy potential. Therefore, the feasibility of producing large-scale green hydrogen at a competitive price is better in these regions with low-cost renewable options. With renewable electricity prices (solar and onshore wind) below US$25 per MWh in countries like Chile, Portugal, Saudi Arabia, and the United States, electrolyzer units can produce green hydrogen with LCOH below US$3.50 per kg (ESMAP, 2020).

IEA estimates installed global electrolyzer capacity of 3585 GW will be required to meet the 2050 net-zero scenario (IRENA, 2021, Cammeraat et al., 2022). The electricity needed to feed electrolyzer units will be about 20% of the world's total electricity supply in 2050, which is more than the world's total available renewable electricity capacity of around 2800 GW in 2020 (IRENA, 2021, Cammeraat et al., 2022). Therefore, adding new renewable electricity capacity in 100s of GW is imperative to support electrolyzer-related electricity demand to meet 2050 net-zero scenarios.

Although grid-connected electrolyzers can result in better capacity utilization and deliver expected production demand, this configuration faces two issues. First, generated hydrogen can only be claimed as 100% green when the origin of consumed electricity from the grid is known. Also, it may be complex to implement green origin tracking and certification system on grids, thus leading to additional costs and on-site energy storage units. Second, consuming grid electricity creates a renewable energy accounting problem for policymakers as existing renewable electricity is diverted to green hydrogen production, which could violate the additionality concept. Renewable energy regulators in many European countries support the additionality concept to avoid the double counting problem. Renewable energy regulators specify that when one energy vector (electricity) is transformed into another vector (green hydrogen), renewable energy use shall be considered only once for accounting purposes. The additionality concept mandates that renewable electricity used in green hydrogen production should differ from the renewable electricity capacity accounted for electricity sector decarbonization (Pototschnig, 2021). Industrial-scale green hydrogen units with off-grid renewable electricity in high-resource locations can address the above issues and provide low-cost green hydrogen.

Consequently, it is more pertinent and cost-effective to set up green hydrogen units where low-cost renewable electricity source is abundantly available (Cammeraat et al., 2022). Although, the off-grid configuration may limit the electrolyzer utilization rate due to the available capacity factors of renewable electricity from solar PV (Photovoltaic) and wind resources, making a business case for green hydrogen from off-grid renewable electricity challenging (IRENA,2018). Nevertheless, the business case for off-grid green hydrogen can be improved by selecting a project site close to favorable meteorological conditions that can deliver renewable electricity with lower LCOE (Levelized Cost of Renewable Electricity) and higher CF (Capacity Factor). Within a region, LCOE varies depending on meteorological conditions. Also, LCOE and CF rely on selected renewable electricity generation technologies. Among onshore solar PV, onshore wind, and offshore wind, the weighted-average LCOE and CF differ widely. IRENA (2022) reported the global weighted average LCOE range for onshore solar, onshore wind, and offshore wind as 0.029 to 0.120 US$/kWh, 0.020 to 0.064 US$/kWh, and 0.054 to 0.127 US$/kWh, respectively (Table-1). While the global average CF for onshore solar PV was at 17.2%, onshore wind was at 33%, and offshore wind was highest at 39% (Table-1) (IRENA, 2022). Within the UK, the weighted-average LCOE and CF vary considerably across different regions for available renewable electricity generation technologies.

Table 1.

Renewable Electricity Costs & Capacity Factors in 2021 (Source: IRENA, 2022)

Renewable Electricity Sources	Weighted-average LCOE US$/kWh	Average CF (%)
Onshore Solar (Global)	0.029 to 0.120	17.2
Onshore wind (Global)	0.020 to 0.064	33
Offshore Wind (Global)	0.054 to 0.127	39

1.2 Aim of the Paper

This paper aims to conduct a high-level business case analysis for off-grid configuration in the UK by reviewing the most cost-effective renewable electricity option based on its impact on the LCOH of green hydrogen. This paper uses the LCOE and CF data trends of renewable electricity generated from solar, onshore wind, and offshore wind in off-grid configurations. I started section 1 with a brief discussion on the LCOH of green hydrogen with renewable electricity as a significant cost factor. Also briefly discussed grid-connected green hydrogen production issues and justified why off-grid configuration would be more appropriate. In section 2, I discuss the methodology and data source used. Section 3 discusses LCOH metrics and its relationship with renewable electricity LCOE and CF, while section 4 highlights cost and CF tend for renewable electricity resources in the UK. In section 5, using an off-grid production model, I assessed different renewable electricity scenarios and analyzed cost and CF impacts on LCOH. In section 6, with a focus on the UK, I discussed and proposed the most cost-effective renewable electricity scenario to improve the business case of off-grid green hydrogen production. Section 7 concludes the paper by highlighting key takeaways from the paper.

2. Materials and Method

A literature review was conducted to conceptualize LCOH metrics and its dependency on renewable electricity LCOE and CF in the off-grid configuration. I developed a green hydrogen economic model in an off-grid mode and considered three scenarios of renewable energy sources (S1: Onshore solar, S2: Onshore wind, S3: Offshore wind). I considered all other cost factors to remain constant for three scenarios as I selected the project location in the UK, and the same electrolyzer unit (capacity and design) was applied to all the scenarios. In this high-level analysis, I assessed the impact of renewable electricity cost and capacity factor on LCOH for each scenario. Data sources from *IRENA, Statista, & BEIS* were used in this study.

3. LCOH Metrics

The LCOH is a metric that indicates the average per unit cost of green hydrogen produced over the plant's lifecycle; it accounts for all of the capital and operating costs of the assets involved in green hydrogen production. LCOH is expressed as the total lifetime cost (Capital investment + Operating & Maintenance cost) incurred divided by green hydrogen produced from the plant.

$$LCOH = \frac{\Sigma\frac{C_{INV}}{(1+r)^t}+\Sigma\frac{C_F}{(1+r)^t}+\Sigma\frac{C_V}{(1+r)^t}}{\Sigma\frac{M_{H_2}}{(1+r)^t}} \tag{1}$$

$LCOH$= Levelized Cost of Green Hydrogen

t=Lifetime of unit

r=Discount rate

C_{INV} =Capital Investment for plant

C_F =Fixed O&M cost

C_V =Variable O&M cost

C_{RE} = Renewable electricity cost

C_{Wat} = Water cost

C_V =$C_{RE} + C_{Wat}$

The hydrogen production M_{H_2}depends on the electrolyzer power rating (E_{ES}) it's efficiency (η) and the load factor of electrolyzer unit. Since, this paper analyses off grid business case without any onsite electricity storage facilities. Therefore, in this case, the load factor of electrolyzer will be the available capacity factor of renewable electricity (C_f) (Stori, 2021).

$$M_{H_2} = \frac{\eta.E_{ES}.C_f}{LHV} \tag{2}$$

E_{ES} = Electrolyzer power rating

C_f = Renewable electricity capacity factor

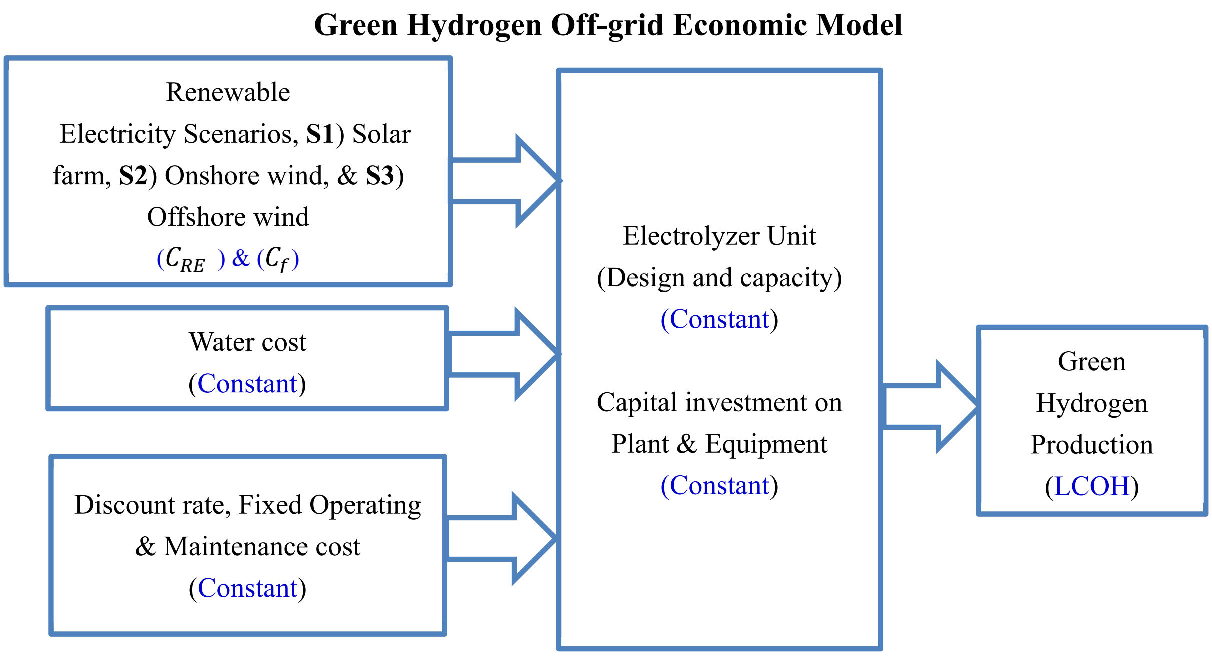
η = Electrolyzer efficiency

M_{H2} = Hydrogen produced

LHV= Lower heating value of hydrogen

The aim of this high-level analysis is to evaluate the impact of renewable electricity cost and capacity factor on LCOH for three scenarios of renewable electricity sources (S1: Onshore solar, S2: Onshore wind, S3: Offshore wind). Therefore, based on equation (1) and (2), it is possible to establish LCOH as a function of renewable electricity cost (C_{RE}) & renewable electricity capacity factor (C_f).

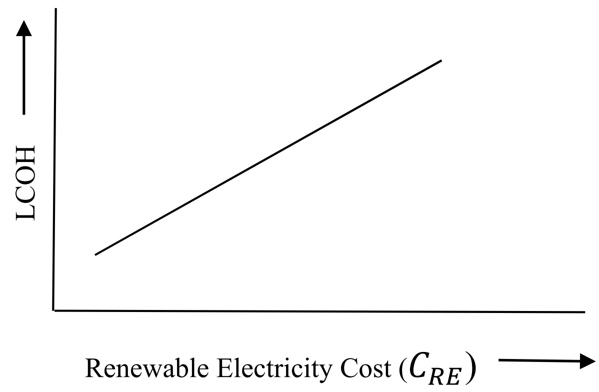
$$LCOH = f\ (\text{Variable\_}C_{RE}\ ,\text{Variable\_}C_f) \tag{3}$$

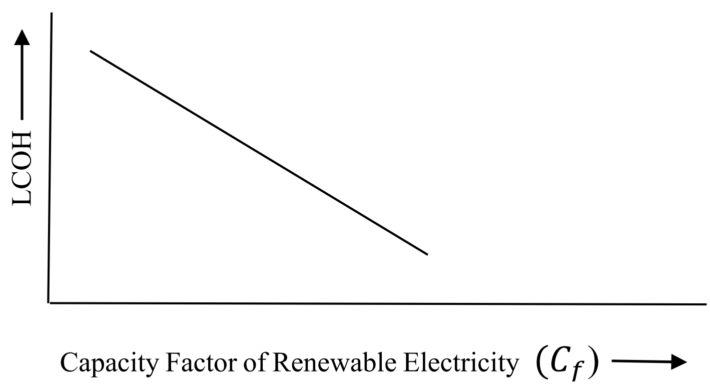


I proposed an economic model for green hydrogen production in off-grid mode considering three scenarios of renewable electricity sourcing S1) Solar farm, S2) Onshore wind, & S3) Offshore winds. To add a geographical context to the model, I selected the United Kingdom as a region of interest for green hydrogen production in off-grid mode. In this model, I assume that discount rate, fixed operating & maintenance cost, capital investment on electrolyzer unit, and water cost remain nearly constant across the UK. Considering all other cost variables remain constant within the selected region, I used reduced form equation (4) to analyze the impacts of exogenous variables (C_{RE} , C_f) on the LCOH as endogenous variables where β_0 is intercept and β_1 & β_2 are coefficients. Longden, Jotzo, and Löschel (2021) used reduced-form marginal effect relationships to analyze the effect of electricity costs, electrolyzer capital costs, and capacity factors on the LCOH of green hydrogen production. The reduced-form approach Maasoumi (1978) proposed is an estimator based on a linear simultaneous equation system (Phillips, 2017). In econometrics, reduced-form models are used to evaluate endogenous variables in terms of exogenous variables. The reduced form is derived formally from a theoretical model in a way that endogenous variables are a function of an unobserved error term and a set of exogenous variables; it is used in studying causal relations between observable variables (Whited, 2022). In contrast to the structured approach used for a deeper understanding of an economic model using a very detailed information set, the reduced form approach based on less detailed information reflects the current understanding of exogenous explanatory variables of interest. Longden et al. (2021) suggested reduced form approach is novel and widely applicable to analyzing parameters that are impacting LCOH.

Reduced Form equation:

$$LCOH = \beta_0 + \beta_1 C_{RE} + \beta_2 \frac{1}{C_f} \tag{4}$$





4. Renewable Electricity in the UK

4.1 Renewable Resource Background

The UK is Europe's second major renewable electricity generator after Germany. Renewable capacity in the UK has increased more than 20 times since 1996, and by 2021, renewable electricity accounted for around 40% of total electricity generated (BEIS, 2022). Wind and solar are two major sources of renewable electricity in the UK; In 2021, the share of wind energy in total renewable electricity generation was 53%, followed by solar energy with a 28% share (IRENA,2022). The renewable electricity generation from offshore and onshore wind was 35.5 TWh and 29.2 TWh, respectively, while solar farms contributed 12.1 TWh (BIES, 2022). With effective market-driven policy instruments like CfD (Contract for Difference), the UK provided an impetus to offshore wind development. According to GWEC (2022), 28 GW offshore wind capacity is planned in the 2022-2026 period for Europe, out of which around 41% of total capacity is likely to be installed in the UK alone, primarily due to CfD policy support.

In the last few years, the North Sea region has emerged as a hotspot of offshore wind farm development due to the availability of strong and reliable wind resources at shallow water depths (Akhtar et al., 2021). However, in general, offshore wind farms' performance is affected by wakes and blockage in wind flow direction due to the presence of turbine arrays downstream. The wakes are generated at the downstream region of a turbine, characterized by usually lower wind velocity and turbulent flow; In contrast, in the induction region before the turbine arrays, turbines act as an obstruction, reducing the wind velocity upstream and deflecting flow, known as blockage (Strickland, 2021). Wakes are not just generated within the wind farm; they can also result from neighboring wind farms located directly upstream. According to Nygaard (2014), offshore wind farms are developed in clusters, where neighboring wind farms impact each other's performance, and recommended wake modeling at the planning stage to minimize wake impacts. Apart from the wake and blockage in wind farms, inherent variability, and lack of predictability of the wind resource are often considered a challenge in wind farm development. The Wind power generation in the UK is typically higher in the winter months and lower during the summer months; the interannual production variation can be significant; a variation of 10%–15% has been typically recorded for onshore Scottish wind power (Potisomporn &Vogel, 2022). There is a trade-off to be made while clustering the offshore wind farms during development. Clustering helps reduce capital costs due to optimized infrastructure, but these advantages can be offset by wind wake effects impacting overall wind farm performance. Akhtar et al. (2021) highlighted that wind resources in the North Sea should be considered a limited resource and emphasized better planning and optimization of locations considering the presence of wind wakes over a multi-year atmospheric condition.

Solar farms are the next largest renewable electricity generators after wind farms in the UK. Solar farms have been the simplest form of renewable electricity generation. Solar panels require low capital costs compared to wind turbines. However, solar farms are marked with low efficiency and seasonal variability. In the UK, solar panels typically have an efficiency of 15 to 20% in converting solar irradiation into electricity, while wind turbines can convert around 60% of wind resources into electricity. Solar farms' outputs are high during summer while lowest during winter seasons. Opponents often criticize the large footprint and aesthetic impact of solar farms. The use of agricultural lands for solar farm development has been debated in the UK. The UK's agricultural land regulation classified lands into the following grades:1 - excellent, 2 - very good, 3a - good, 3b - moderate, 4- poor, and 5- very poor. Usually, setting up a solar farm on land classified as agricultural grade 1, 2, or 3a is unlikely to get permission. Palmer et al. (2019) highlighted that most current solar farms in the UK are located on agricultural land grades 1, 2, and 3, with 16% of solar farms falling into grade 1 and 2 areas. The main reason is that the available solar irradiation in the UK is concentrated on one-third of the UK's mainland, covering the UK's southwest, southeast, and midlands. At the same time, two-thirds of the UK has limited solar energy resources. Palmer et al. (2019) stated that the business case for solar farm development remains encouraging in sites located in the south, southeast, and east of the UK and suggested using Geographical Information Systems (GIS) modeling techniques to discover economically feasible locations for large-scale solar farms.

4.2 Cost and Capacity Factor

Globally, renewable electricity costs have been reduced while generation efficiencies have improved over the last decade as wind and solar technologies have matured. IRENA (2022) data on renewable electricity generation cost shows, in the UK, the cost (US$/kWh) of utility-scale solar power dropped by 87% in 2021 (0.069 US$/kWh) compared to 2010 (0.534 US$/kWh) while offshore wind electricity cost dropped by 74% in 2021 (0.054 US$/kWh) from 2010 (0.210 US$/kWh). Such drastic cost reduction can be attributed to technological and operational learning in the industry over the years. On the one hand, the improved efficiency of wind turbines and solar panels supported the economy of scale that helped set up large-scale generation units with lower operating costs. On another side, renewable electricity project operating life cycle improved significantly to around 25 years for wind farms and 35 years for large-scale solar farms due to improved reliability and lower equipment downtime (BEIS, 2020). Such factors helped the renewable sector reduce LCOE for renewable electricity from wind and solar. Additionally, project financing costs have been reduced over the years, helping developers take up projects with lower financial risks. The hurdle rate, the weighted average cost of capital (WACC), is the minimum financial return a project developer would require over a project's lifetime in the UK. Hurdle rates have declined since 2016; lower hurdle rates have lowered LCOEs (BEIS, 2020). The UK's renewable electricity cost has fallen drastically in over ten years.

Table 2.

Utility scale Solar Electricity Weighted Average Cost (US$/kWh) (IRENA,2022)

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2010-2021 change
United Kingdom	0.534	0.493	0.290	0.235	0.192	0.150	0.142	0.116	0.118	0.088	0.075	0.069	-87%

As shown in Table-2, the weighted average cost (US$/kWh) for utility-scale solar electricity was US$/kWh 0.069 in 2021, almost an 87% reduction from the 2010 level. Similarly, the LCOE of onshore wind electricity reduced by almost 59% in 2021 from 2010 (Table-3).

Table 3

Onshore Wind Electricity LCOE (US$/kWh) (IRENA,2022)													
Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2010-2021 change
United Kingdom	0.1023	0.105	0.0937	0.0932	0.0881	0.0804	0.0696	0.0661	0.0462	0.0565	0.0457	0.0422	-59%

Like solar and onshore wind, the LCOE of offshore wind has fallen drastically over the last ten years. The rapid development of offshore wind technology resulted in reduced capital and operating costs, and large-capacity turbines improved economies of scale (BEIS, 2020). North Sea counties like Denmark, Germany, and the UK have benefited from offshore wind technology developments. As indicated in Table-4, between 2010 and 2021, the LCOE of offshore wind electricity in Demark, Germany, and The UK reduced by 62%, 54%, and 74%, respectively. The LCOE of offshore wind electricity in the UK (0.054 US$/kWh) is the lowest in the global range of 0.054 to 0.127 US$/kWh, making it the cheapest among countries with high wind resources (IRENA,2022).

Table 4.

Offshore Wind Electricity LCOE (US$/kWh) (IRENA,2022)			
Country	Year 2010	Year 2021	2010-2021 change
Denmark	0.108	0.041	-62%
Germany	0.179	0.081	-54%
United Kingdom	0.210	0.054	-74%

Table 5.

Capacity Factors in UK (Fernández, 2023a & 2023b) *Retrieved from Statista- data source BEIS (2022)*			
Year	Onshore wind	Offshore Wind (in %)	Solar PV
2010	21.90	30.50	7.60
2011	27.90	37.00	5.10
2012	25.80	35.80	11.20
2013	28.40	39.10	9.80
2014	26.20	37.30	10.90
2015	29.30	41.50	11.40
2016	23.60	36.00	11.00
2017	28.00	38.90	10.60
2018	26.70	39.90	11.20
2019	26.50	40.40	10.70
2020	28.30	45.70	10.90
2021	23.20	37.40	10.00
Median	26.6	38.2	10.7
Average	26.3	38.3	9.9

Another critical parameter of renewable electricity systems is the capacity factor, a measure of electricity produced by a plant divided by its maximum rated installed capacity. It widely varies with meteorological conditions of plant location and also depends on renewable energy technologies. Table-5 shows the capacity factor for onshore wind, offshore wind, and solar PVs in the UK between 2010 to 2021. In the UK, the median capacity factor of solar farms is 10.7% which is below the global average of 17.2% reported in 2021 (IRENA, 2022). In contrast to solar farms, the median capacity factor of onshore wind and offshore wind farms are found to be much higher, with values of 26.6 % and 38.2%, respectively. As indicated in Table 5, the capacity factors of onshore and offshore wind were reported lower in the year 2021 compared to the period between the year 2017 to 2020. The lower capacity factors for onshore and offshore wind in 2021 can be attributed to low wind resources.

As indicated in Table 6, within the UK, the East and South-East regions of England have much higher capacity factors for offshore wind than other regions. Wales, South-East, and East Midlands have marginally better capacity factors for onshore wind. While the South of England and Wales have better capacity factors for solar farms than other regions. The capacity factors for specific renewable technology are not constant in the UK but vary with meteorological conditions. The capacity factor variability for renewable technologies in the UK can provide significate insight to green hydrogen developers in selecting plant locations in an off-grid configuration. The capacity factors of onshore and offshore wind farms are expected to improve further in coming years with the use of large capacity turbines, which will have better wind access due to increased height and efficiency. According to BEIS (2020), report capacity factors of offshore wind farms in the UK are expected to improve significantly with an increase in turbine size and projected that it can reach up to 57% by 2030 with the use of 15 MW turbine size and 63% by 2040 with 20 MW turbine size.

Table 6.

Region Wise Capacity Factor in the UK (BEIS, Sept 2022)

Region	Onshore Wind	Offshore Wind	Solar PV
England	**23.3%**	**38.5%**	**10.1%**
East Midlands	24.2%	29.9%	10.0%
East of England	23.9%	41.3%	10.2%
North-East	22.3%	34.8%	9.5%
North-West	22.7%	35.1%	9.6%
London	14.4%	-	9.2%
South-East	24.2%	37.3%	10.3%
South-West	22.9%	-	10.3%
West Midlands	21.6%	-	9.8%
Yorkshire and the Humber	23.7%	-	9.6%
Northern Ireland	**22.2%**	**-**	**9.5%**
Scotland	**23.1%**	**33.8%**	**9.0%**
Wales	**25.6%**	**29.3%**	**10.4%**

(-) Data not available / Not reported

5. Impact Analysis

The economic model for green hydrogen production in an off-grid configuration based on three scenarios of renewable electricity sourcing S1) solar farm, S2) onshore wind, & S3) offshore wind were analyzed in this section. The model assumes that discount/hurdle rate, fixed operating & maintenance cost, capital investment on electrolyzer unit (design and capacity), and water cost will remain constant in all three scenarios across the UK. Only two variables C_{RE} and C_f depending on selected renewable electricity sources will affect the LCOH. I used reduced form equation (4) to analyze the impacts of exogenous variables (C_{RE} , C_f) on the LCOH.

For renewable electricity cost (C_{RE}) impact analysis I used 2021 UK LCOE for all three scenarios from IRENA 2022 data source (table-2,3 & 4)

C_{RE} (Solar) =0.069 US$/kWh

C_{RE} (Onshore Wind) =0.0422 US$/kWh

C_{RE} (Offshore Wind) =0.054 US$/kWh

Among these three scenarios, renewable electricity costs from solar farms C_{RE} (Solar) would likely increase LCOH. In contrast, electricity cost from onshore wind farms will tend to lower the LCOH in the UK. The electricity cost from offshore wind will have a lesser impact on LCOH increase than electricity cost when sourced from solar farms.

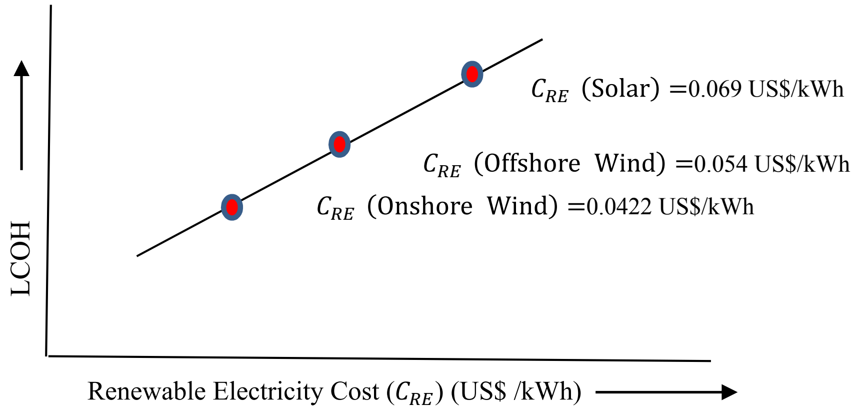


Figure 1

For Capacity factor (C_f) impact analysis I used median of data from 2010 to 2021 (Table-5). To avoid any skewness in the data median is preferred measure of central tendency.

C_f(Solar)= 10.7%

C_f(Onshore Wind) =26.6%

C_f(Offshore Wind) =38.2%

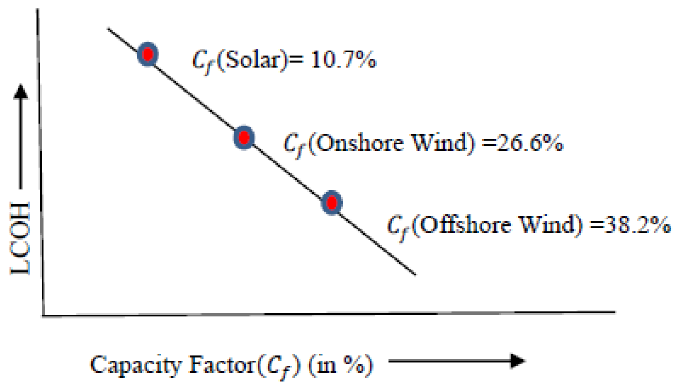


Figure 2

Among three scenarios, C_f(Solar) would increase LCOH whereas C_f(Offshore Wind) is likely to bring down LCOH in the UK. The C_f (Onshore Wind) is likely to have a lesser impact on LCOH increase compared to C_f(Solar).

6. Discussion

To conduct a high-level business case analysis, I reviewed impacts of renewable electricity options on the LCOH of green hydrogen in off-grid configuration, I analyzed three scenarios S1) Solar farm, S2 Onshore wind, & S3) Offshore winds in the UK. I observed that among the three scenarios, due to higher cost and lower CF, scenario S1 (solar farm electricity) will increase the LCOH in an off-grid configuration. The highest cost (0.069 US$/kWh) and lowest CF (10.7%) of solar PV-generated electricity are understandably due to the lower solar potential in the

UK. The annual electricity generation per unit of installed PV capacity (MWh/kWp) in the UK is below 1.2 compared to South European countries like Spain and Portugal (IRENA, 2022b). Spain has higher solar potential than the UK, with the annual electricity generation per unit of installed PV capacity (MWh/kWp) at 1.6, making it the best choice for green hydrogen in Europe (IRENA, 2022c). Solar electricity with reduced cost and improved CF can be a cost-effective option for green hydrogen generation in North Africa and the Middle East due to higher solar potential. In the Middle East region, UAE, with an annual electricity generation per unit of installed PV capacity (MWh/kWp) of 1.9, can generate low-cost solar electricity at improved CF (IRENA, 2022d).

The observation corroborates with recent research studies exploring the prospects of solar PVs to feed green hydrogen-producing units. According to Sarker et al. (2023), although solar is a clean and abundant energy source, however, unable to meet electrolyzer demand due to lower CF; hence, solar electricity may not be the best choice in countries with low solar potential. As electricity costs continue to drop, solar PVs can be used in a hybrid system with onshore wind energy, which can address cost and CF issues in the UK. from a Solar farm developer's perspective, the solar farm proposal must pass through multiple criteria before getting planning permission. Typically, in the UK, for every MW of solar electricity, 5 acres of land need to be considered, and land should be ideally flat or south-facing slope to get the best performance; this could impede utility-scale solar farm development (Palmer et al.,2019).

Scenario S2 (onshore wind electricity), with the lowest cost and higher capacity factor than Solar PVs, would reduce the LCOH. The lowest cost (0.0422 US$/kWh) with high CF (26.6%) of onshore wind electricity is due to high wind potential in the UK. According to (IRENA, 2022b) majority of the UK's land areas have much higher wind power density at 100m height (W/m2) compared to the global average making it most suitable for onshore wind electricity. However, over the last decade, there have been conflicting opinions and debates surrounding perceived social, environmental, and economic impacts/benefits of onshore wind farm development in the UK. the contentious issues that aggravate community concern are 1) noise generated from turbines, 2) property price impacts near a wind farm, 3) direct economic or social benefits and 4) environmental impacts (Wilson & Dyke; 2016). To address such concerns, the UK government in 2016 enacted onshore wind farm policy changes that allowed local community involvement in the onshore wind farm planning phase and gave them more decision-making power on the siting of onshore wind farms across the UK (Mordue et al., 2020). However, such decentralized decision-making induced delays in onshore wind farm planning permissions. According to GWEC (2022), in the UK, Onshore wind farm development must meet strict planning requirements, but local authorities lack the guidance to mobilize community support; between 2016 and 2020, only 16 turbines in 7 locations received planning permission.

Scenario S3 (offshore wind electricity), with the highest capacity factor and lower cost than Solar PVs, will substantially reduce the LCOH. With a cost (0.054 US$/kWh) and the highest CF (38.2%), offshore wind electricity can be the most compelling option to feed electrolyzers in the UK. This observation corroborates the latest knowledge in green hydrogen development. According to Dawkins, Ash, and Suvendiran (2022), identifying the lowest cost of renewable electricity with a higher capacity factor is critical in the off-grid configuration, enabling electrolyzers to operate for a long time and bring down the LCOH. Scottish government's assessment report (2020) on offshore wind to green hydrogen opportunity highlighted that a significant contributor to green hydrogen LCOH is renewable electricity cost and identified offshore wind potential in the North Sea as a compelling cost advantage for green hydrogen production in the UK.

Due to the technological enhancement in wind turbine design in the last few years, large-size turbines (15MW and 20MW) are expected to improve the capacity factor further. BEIS (2020) report, based on turbine specifications from manufacturers and available wind data in the UK, projected that in the future, turbines with 15 MW size could result in a capacity factor of 57%, and turbines with 20MW can produce wind electricity with a capacity factor of 63%.

The North Sea has emerged as a hotspot of offshore wind farm development motivated by the strong and reliable wind resources at shallow water depths (Akhtar et al., 2021). The low cost of offshore wind generation results from wind resource availability in shallow water near the shore (Jansen et al., 2022). Most offshore wind farm development occurs in shallow water, and available sites in shallow water are getting exhausted due to massive developments, future project sites must be located far from shore in deep water (Bosch et al., 2019). As future offshore wind farm development is likely to be in deeper water away from the shore, this could lead to higher LCOE due to increased electricity transmission costs and higher operation and maintenance costs due to the rough sea conditions. Also, offshore wind electricity generation cost depends on the distance to the coast and water depth (Bosch et al., 2019). One of the technical challenges is transmitting electricity back to shore. Traditional AC power cables have higher capacitance and, hence, higher transmission losses. More recent High Voltage Direct Current

(HVDC) systems have come up to overcome this challenge, which is expensive as converter stations are required at both ends of the transmission line (Calado et al., 2021). HVDC technology is recommended only for longer distances (above 50 km) because of expensive converter substations at both ends of power transmission (Jansen et al., 2022). Since most offshore wind resources are located in deep waters in the range of 50-100km from shore, HVDC has emerged as the most preferred technology to prevent transmission losses. However, HVDC adds to CAPEX and OPEX costs and other technical complications. Industry experts and researchers support the offshore wind energy-to-hydrogen concept to overcome power transmission related costs and technical challenges. In this concept, green hydrogen will be produced offshore near the wind farm and further compressed and transported onshore through the pipeline. From an economic perspective, Calado et al. (2021) argued that pipelines have larger transmission capacity than cables, resulting in lower normalized capital costs compared to offshore electrical cables to transmit the same amount of energy.

In the last 2-3 years, researchers started exploring alternate pathways to produce green hydrogen from offshore wind resources. Dawkins et al. (2022) identified a centralized system where green hydrogen-producing electrolyzers co-located and directly connected with an offshore wind electricity source as the most cost-effective pathway to reduce the impact of renewable electricity cost and capacity factor. The green hydrogen produced offshore can be compressed and transported onshore through the pipeline. In the study exploring the UK's wind-to-hydrogen potential, Giampieri et al. (2023) found that green hydrogen produced offshore with wind electricity, compressed, and transported to shore through the pipeline will be the most cost-effective scenario from 2025. However, the economic feasibility of this scenario depends on the storage period and the distance to the shore of the offshore wind farm. Calado et al. (2021) identified the high cost and technical challenge of transmitting electricity onshore and proposed a cost-effective centralized system where green hydrogen is produced, compressed, and transported in a pipeline to shore.

In recent years the offshore wind-to-hydrogen concept has started picking up in European countries. The NortH2 project, based on cross border consortium of Eneco, Equinor, RWE, and Shell Netherlands, plans to set up an integrated wind-to-green hydrogen value chain in The North Sea and aims to produce 1 million tonnes of green hydrogen by 2040 (NortH2, 2022). Along similar lines, the Netherlands and Germany initiated a feasibility study for Hy3 – Large-scale green hydrogen production from offshore wind. The feasibility study aims to investigate the potential for green hydrogen production in the offshore and coastal regions of the Dutch and German North Sea and develop a green hydrogen value chain to meet decarbonization targets in both countries (DENA, 2022).

The UK government has set an ambitious plan to add 50GW of offshore wind energy capacity by 2030. However, there needs to be more focus on improving the existing national grid infrastructure to tap huge wind potential in the North Sea. As most of the UK's offshore wind potential is found in the waters of East and South-East regions of England, North of Scotland, and Wales, the limited grid infrastructure in these areas could fail to deliver power to high-demand regions across the UK. In the UK, grid infrastructure constraints also lead to substantial offshore wind curtailments meaning loss of actual renewable energy potential, which could have contributed to the decarbonization initiatives. In addition to grid infrastructure issues, curtailments in wind farms also happen due to supply and demand imbalance as a result of extreme wind conditions leading to either large or very small volumes of power being fed into the grids.

The amount of offshore wind electricity curtailment is expected to increase by adding a new 50GW offshore wind electricity capacity by 2030 without significantly improving current grid conditions in the UK (Giampieri et al., 2023). One way to address the grid constraint issue and overcome offshore wind-related curtailments in the UK is to co-produce green hydrogen with offshore wind electricity. Most researchers agree that a part of the total offshore wind electricity capacity should be utilized to co-produce green hydrogen. According to Stori (2021), offshore wind energy-to-hydrogen can reduce curtailments if excess offshore wind output is transformed into green hydrogen. According to Calado et al. (2021), offshore wind energy-to-hydrogen helps reduce curtailments and potentially reduces LCOH. As an alternative to selling entire offshore wind electricity to the grid at a wholesale rate, a part of the electricity generated by offshore wind farms can be used to produce green hydrogen and transported to shore through pipelines (Giampieri et al., 2023). There are multiple pathways to produce green hydrogen from offshore wind; however, economies of scale and cost-effectiveness across the complete supply chain must be evaluated while selecting the appropriate pathway (Dawkins et al., 2022).

7. Conclusions

The paper conducted a high-level business case study for green hydrogen in off-grid configuration in the UK based on the renewable electricity cost and capacity factor impact on the green hydrogen LCOH. The study observed that renewable electricity from offshore wind is the most cost-effective option for producing green hydrogen in the UK. Since the observations in this high-level business case study are based on a reduced form method using a set of assumptions; therefore, a further quantitative analysis using a structured approach with a detailed set of information on the green hydrogen economic model is recommended. The paper also observed that the renewable electricity capacity factors of solar, onshore wind, and offshore wind depend on the selected site's meteorological conditions. Taking into consideration, green hydrogen-producing units in the off-grid configuration must be located near favorable meteorological conditions to exploit higher capacity factors. The paper also discussed how offshore wind to green hydrogen in an off-grid configuration could be the most effective pathway to bring down the green hydrogen LCOH and overcome wind curtailments in the UK.

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