UK Energy Analysis & Wind Farm Feasibility Report

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Executive Summary

This report will detail the historic trends of electricity generation in the UK from the period of 2012 – 2021. A prediction for 2050 of the likely sources of renewable electricity to displace fossil fuels will follow. Several key factors and sectors will be analysed to forecast electricity demand in 2050. Next, a concept design of a wind farm will be proposed to generate 200 GWh / yr in Scotland, the methodology will be explained and justified. Since renewables are intermittent, solutions will be recommended stemming from forecasts, with practical examples of where and how they have been implemented. A thorough environmental impact assessment will follow looking at positive and negative impacts throughout different phases of wind turbines, furthermore, the effect of climate change on the output of wind power will be discussed. Finally, cost estimation will be carried out for the proposed wind turbine.

Renewable energy's contribution to the UK energy mix is growing rapidly with wind showing the largest annual growth rates. Coal is on a large decline and its complete elimination from the energy mix is imminent. Large-scale solar and wind are both projected to have the lowest levelized costs and thus making them competitive with fossil fuels making it possible for them to displace fossil fuels by 2050.

The total electricity demand is expected to increase to 463 TWh in 2050 which may be a result of an advancing economy and a shift in policies which changes social perception. Improvements in technology in the form of heat pumps and renewable energy storage devices will drive domestic and commercial heating to be mostly electrified. Electric vehicles are bound to transform the transport sector. Natural gas will still be utilized but for the purpose of creating hydrogen and ammonia.

The wind turbine was chosen to be set up on the Isle of Lewis, due to its high wind speeds. The location was also based on the proximity to a substation. 18 wind turbines rated at 3.45 MW are required to meet a demand goal of 200 GWh / yr, with a capacity factor of 36%. Ice removal systems are integrated due to the potential safety and inefficiencies that can be experienced by the turbine and generator. The final layout requires 5km squared to sit the turbine far enough apart to reduce wake losses.

The recommended solution to intermittency is Li-ion batteries due to its vast drop in levelized cost of electricity, which Scotland is building a 400MW facility. Another recommendation is creating hydrogen since wind fuelled hydrogen is the least carbon-intensive.

The main environmental impact of wind turbines is bird and bat fatalities are likely, shadow flicker can be a visual annoyance alongside noise pollution. Wind turbine-induced turbulence can increase the surface temperature by 0.724°C in the vicinity and potentially alter the microclimate near the wind turbine. Rare earth metals may be released into the atmosphere or leach into bodies of water. Decommissioning wind turbines mostly consists of recycling but the blades themselves tend to be landfilled. The direct impact of global warming negatively impacts wind energy output by decreasing wind speeds and thus the UK is set to lose 3% of its output by 2050.

Cost estimations have shown a levelized cost of electricity of £0.055 per kWh and a payback period of 10 years. Windfall tax has to be implemented until 2028 at a rate of 45% over a revenue limit, but an impressive total net profit after tax in 15 years of £148 million is observed.

Q1) Historic Trends of electrical power in the UK

Figure 2 depicts the historic trends of energy generation in the UK from 2012 to 2021 taken from the department for business, Energy & Industrial Supply. Electricity generation from coal has experienced a 95% reduction since 2012 which is the largest across all forms of energy, this can be attributed to coal being the largest contributor to greenhouse gases as seen in Figure 1. A 58% decrease in the periods of 2015 and 2016 due to the increase in tax rate of the Carbon Price Support; a carbon tax [1]. Policies in the UK have created unfeasible conditions to create new coal power plants since carbon capture technology needs to be implemented which tends to dilute the economic benefits of coal-based electricity production [2].

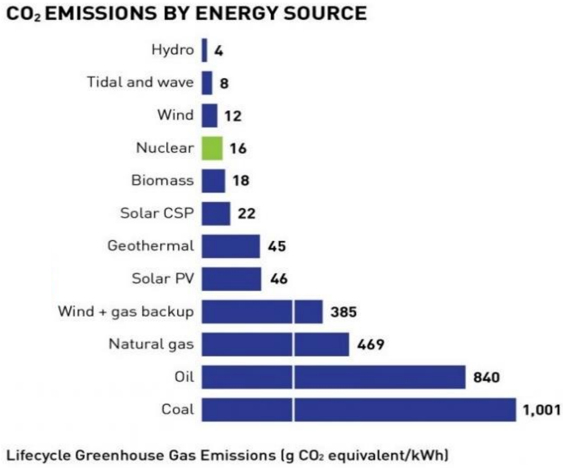

Figure 1 Emissions from various energy sources [59]

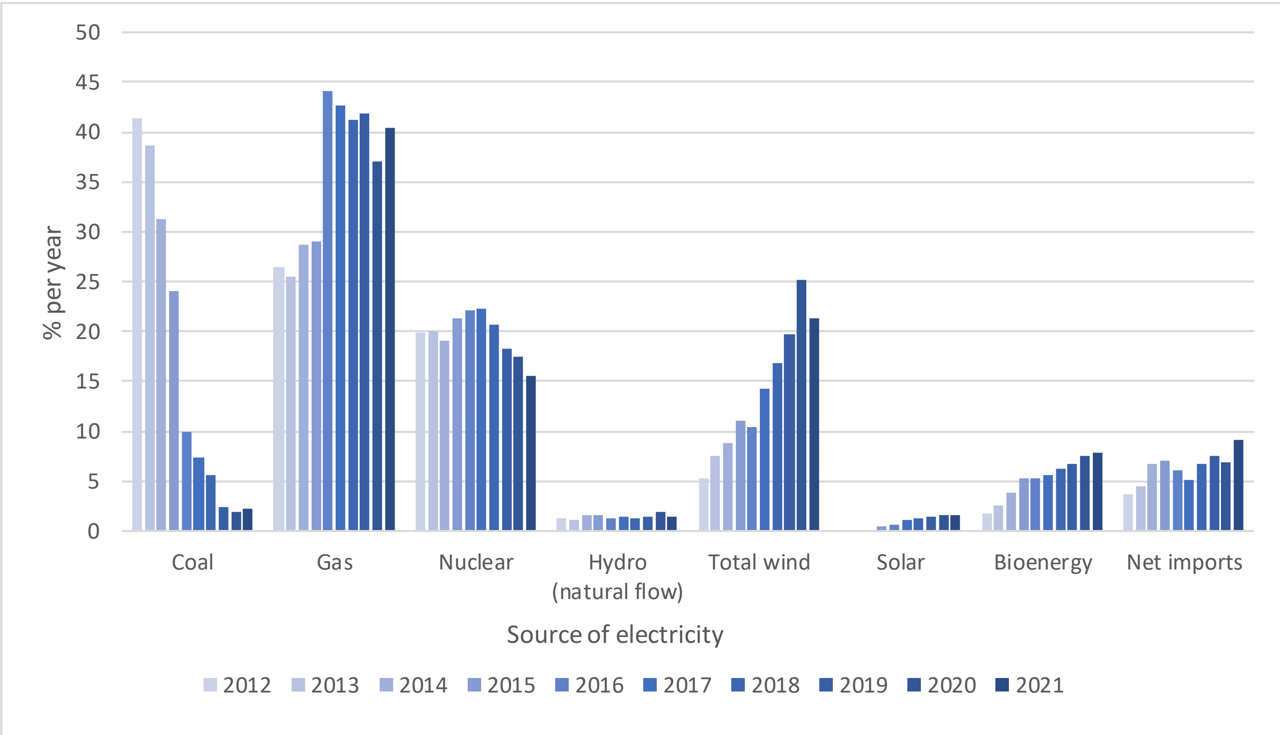

Figure 2 UK Electricity sources percentage contributions per year [67] [68]

Nuclear power has been a stable source of energy used to meet baseline demands, this can be explained by the long lifespan of the reactors and slow response time to meet demands. Despite its past, nuclear energy contributed a mere 15% in 2021 which is the lowest since 2012. Figure 3 depicts the rapid expansion of nuclear energy starting around the 1970s. Nuclear reactor lifespans are around 40 years which is the main reason for the rapid reduction in nuclear energy output observed in the period of 2000 – 2020 since reactors are nearing their end of life.

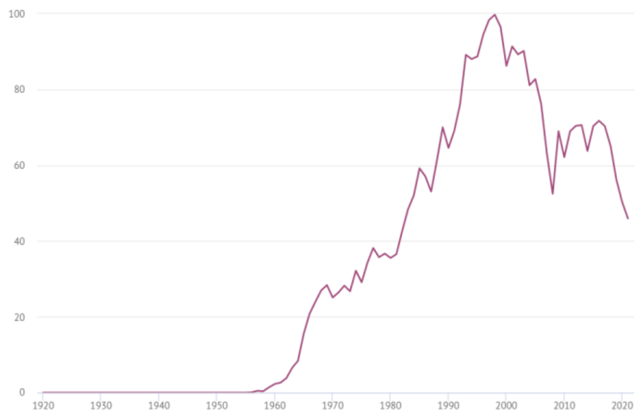

Figure 3 UK nuclear reactor output [61]

Natural Gas has emerged as the main contributor to the energy mix, this can be attributed to its relatively stable and inexpensive cost until 2020 when the price has been extremely volatile [3] which can be linked to geopolitical events. The drop in 2020 is most likely linked to the COVID–19 pandemic since there was a rapid decrease in demand but a surplus of supply. Even though natural gas is a non-renewable and carbon-emitting source of energy it can create grey hydrogen, which itself is a non-carbon emitting fuel. Blue hydrogen also stems from natural gas but utilizes carbon capture technology to further decrease its emissions. The UK produces 700,000 tonnes of hydrogen annually [4] which is most likely blue and grey hydrogen due to their lower cost per mass when compared to their renewable-based counterpart, green hydrogen [5]. As a result of this natural gas is expected to still be a major source of energy in the coming years. The increase in natural gas can also be attributed to the increased efficiency of extraction (as seen in Figure 4) further decreasing costs.

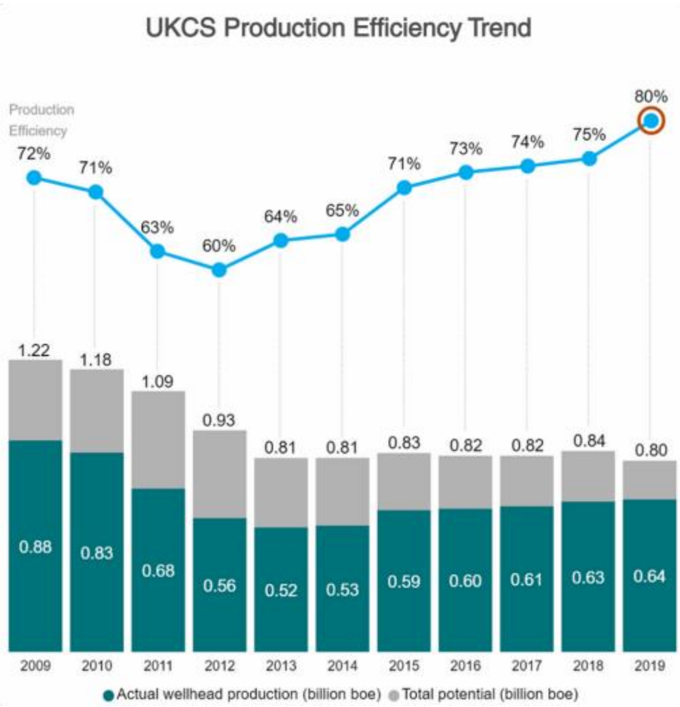

Figure 4 Efficiency of Natural Gas extraction [60]

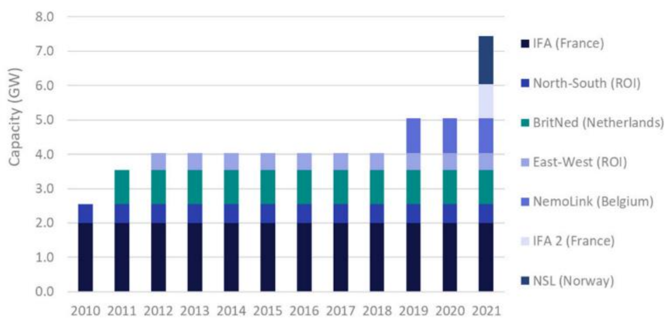

Figure 5 Interconnector Capacity in the UK [62]

Net imports of electricity have increased by 147% since 2012. This is due to the increasing installed capacities of interconnectors (Figure 5) which have the ability to transmit electricity over large distances from and to neighbouring countries. Interconnectors have the ability to transmit excess energy from renewable sources such as wind which bypasses the need to store electricity due to its intermittent nature, 2021 observed 24 TWh of net imports which was most likely used to cover the loss in supply through wind which decreased by 4% compared to 2020.

Renewable energy (excluding nuclear) has experienced drastic net increases in its contribution to the energy mix, with the best year being 2020 producing a total of 95 TWh.

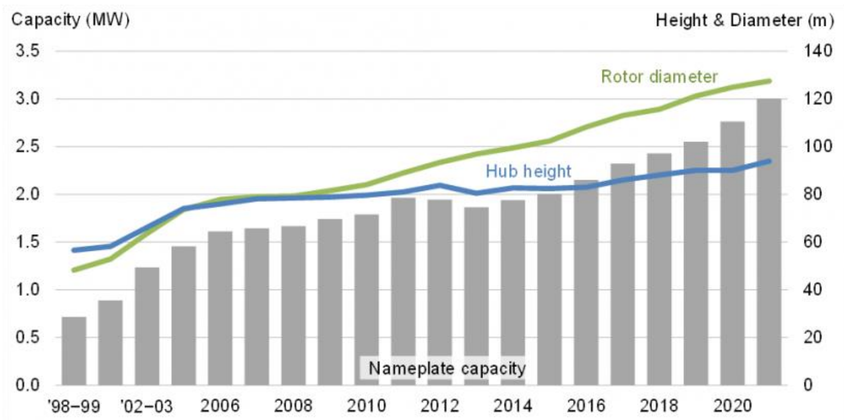

Figure 6 Average Nameplate Capacity, Hub Height, and Rotor Diameter [4]

Wind energy has shown the largest boom in energy generation with an average 20% increase yearly through 2012 – 2021. This is due to the rapid advancements in the nameplate capacity of wind turbines stemming from larger hub heights and rotor diameters as seen in Figure 6.

Despite the increasing installed capacity of onshore and offshore wind (Figure 8), 2021 experienced the first decrease within the last decade which resulted from the lowest annual wind speeds since 2010 (as seen Figure 7).

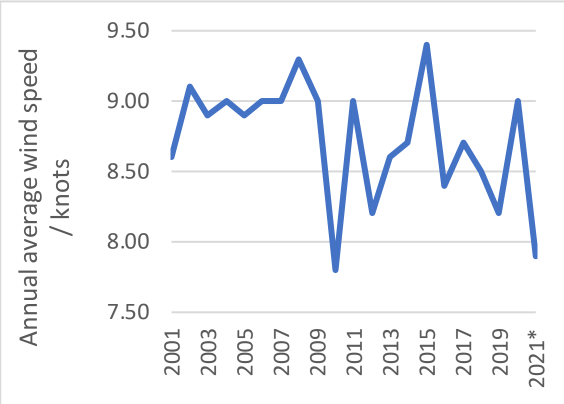

Figure 7 Annual average wind speed in the United Kingdom (UK) from 2001 to 2021 [66]

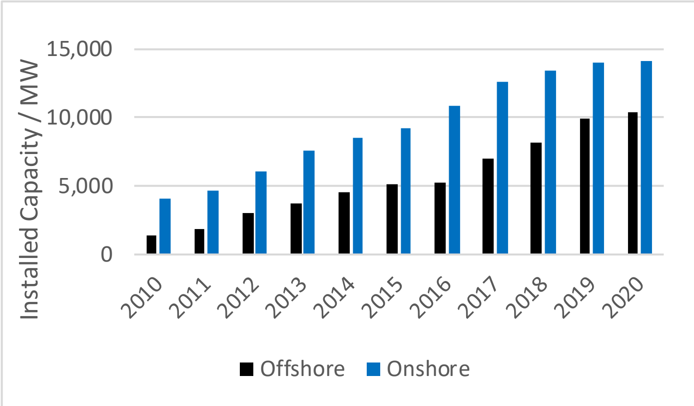

Figure 8 Installed Capacity of wind farms throughout the years in the UK [64]

Solar Power has been on a steady increase with an average of 3 TWh increase yearly only experiencing a drop in 2021 of 1% compared to 2020.

The feed-in tariff scheme introduced in 2010 has contributed to the increase of electricity from solar power by incentivising the installation of renewables for households and businesses. Domestic solar PV installation tends to be less than 4kW. It can be observed from Figure 9 that a large proportion of the UK's solar capacity is from domestic solar pv's, which shows the feed-in tariff scheme is a key driver of solar capacity in the UK.

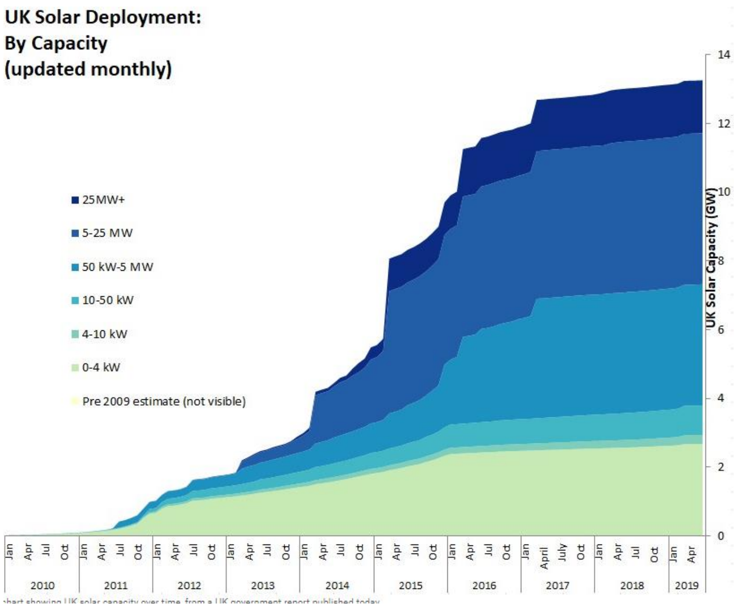

Figure 9 Solar PV capacity in the UK [69]

Bioenergy is a strong contender to decarbonise the energy mix, with an average annual growth of 5%; used to meet baseline loads of electricity demand. 2021 observed the peak of electricity through bioenergy at 21 TWh, matching onshore wind production in 2021. The University of Manchester states "The UK has the potential to generate up to 44% of its energy from biomass sources, including household waste, agricultural residues and home-grown biofuels by 2050" [6], which correlates to its strong growth rate.

Hydropower has been a small yet consistent part of the energy mix, with an average of 1.4% contribution from 2012-2021. The number of sites for hydropower increased, and yet the electricity generated didn't match this and stayed constant [7]. Nonetheless, there is still a small yet significant opportunity in the future for hydropower in the small-scale form to create an additional 850 – 1550 MW capacity [8].

Q1.2) Renewable Generation Sources with the potential to displace fossil fuels towards 2050

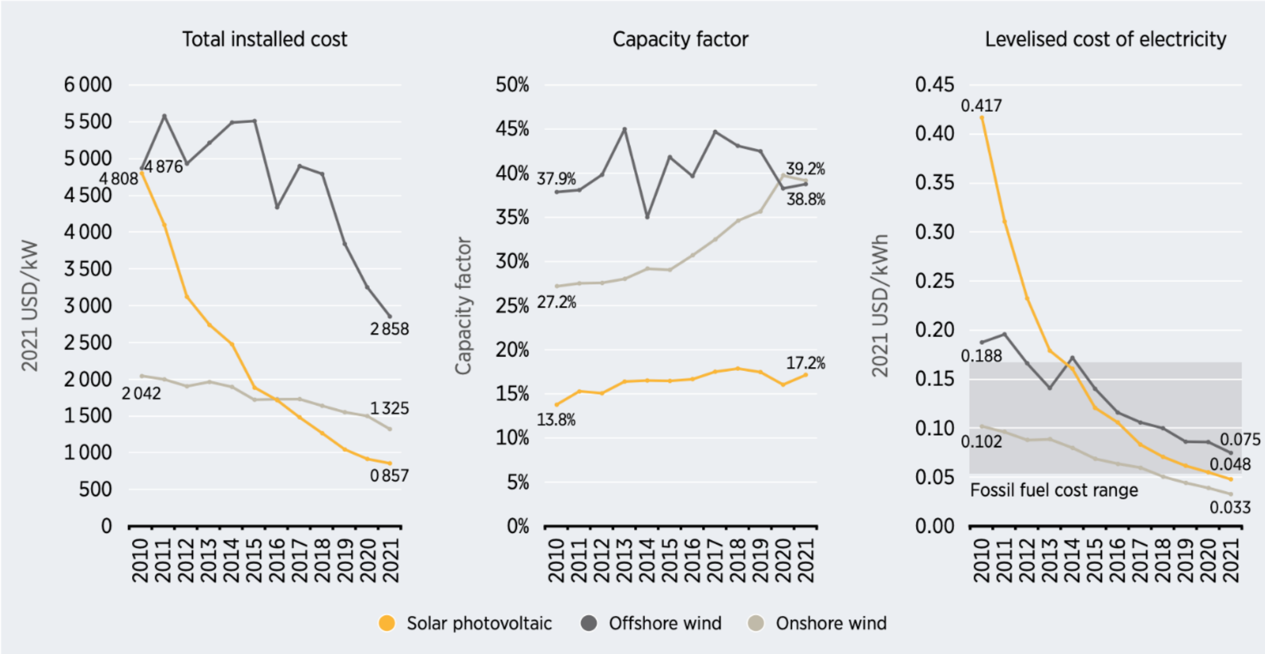

Figure 10 Global weighted average, total installed costs, capacity factors and LCOE for solar and wind [9]

Historic trends shown in Figure 10 show that wind has the greatest potential to be a key player in displacing fossil fuels. The levelized cost of electricity for wind has reached prices which are competitive with fossil fuels, which stems from technological advancements in the form of higher capacity factors relative to solar pv [9]. The total installed costs for offshore wind are rapidly decreasing relative to solar and onshore and this can be attributed to more efficient manufacturing techniques [10].

Additionally, looking into the future, a study has analysed data from BEIS and predicted that the levelized cost (Figure 11) for offshore wind will surpass onshore wind by 2035 and large solar will be match onshore wind by as soon as 2025 and lead on to be the cheapest in 2040, this is spurred by new innovations such as agrivoltaics, floating solar farms that can give outputs similar to a gas and nuclear power plants, improvements in solar cell efficiencies; particularly perovskite solar photovoltaic (PV) cells and new solar coatings which concentrate light beams to achieve efficiencies of 30% [11].

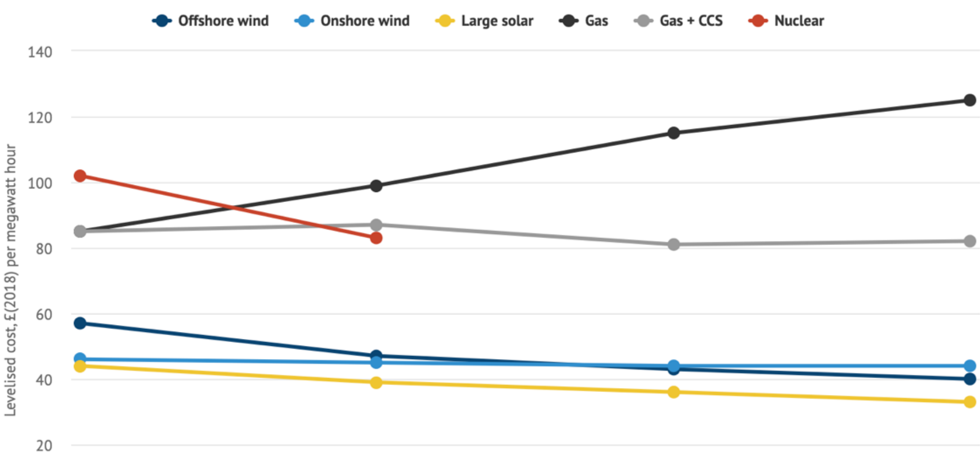

Figure 11 Levelized cost estimates for electricity generation in 2025-2040, in £ (2018) per megawatt hour, for a range of different technologies in the UK [10].

Q2) Predictions for demand for electricity may change from 2023 to 2050.

Several scenarios have been modelled to predict the energy demand in 2050 but there are two main ones which predict the best outcomes for the UK. The 2 degrees scenario takes into account higher low-carbon technology investments, a society which is more conscious about the climate, implementation of policies which make fossil fuel use uneconomical and changes to consumer demands which promote low emissions [12], with the aim of keeping the global temperature beneath 2 degrees °C.

Currently, there is more demand for natural gas than electricity across all sectors, this is expected to reverse by 2050 through the implementation of new policies such as a ban on the sale of internal combustion vehicles which increase the demand for electric vehicles [13]. The peak and total demand are set to decrease, policy changes incentives and a predicted GDP increase of 2.1% which drive technological advancements [12]. This will increase energy efficiency for households by implementing time tariff schemes which will variably change the cost of electricity, better insulation, and the installation of 23 million heat pumps [12] and smart energy monitoring systems. Natural Gas will be part of the energy mix, but for the purposes of creating blue and grey hydrogen. The population is expected to grow substantially with an 80% increase in the population from 2030 to 2050 and an additional 2 million homes in the same period [12]. Energy storage is also expected to increase with 25% of households implementing thermal storage units [12]. 20% efficiency across industrial and commercial sectors is also forecasted [14].

The transport sector is en route to total electrification. Figure 12 depicts the forecasted trend of the growing number of electric vehicles, where a transition period from internal combustion to pure electric vehicles occurs with an intermediate phase of the use of plugin-hybrids [12]. Autonomous driving technology has the possibility to reduce the electricity demand increased by the use of electric vehicles by increasing route sharing seamlessly [12]. An emerging technology that has the potential to decrease peak electricity demand is vehicle-to-grid services which discharge electricity from EV's during peak demand times and recharge EV's when the demand has decreased [12].

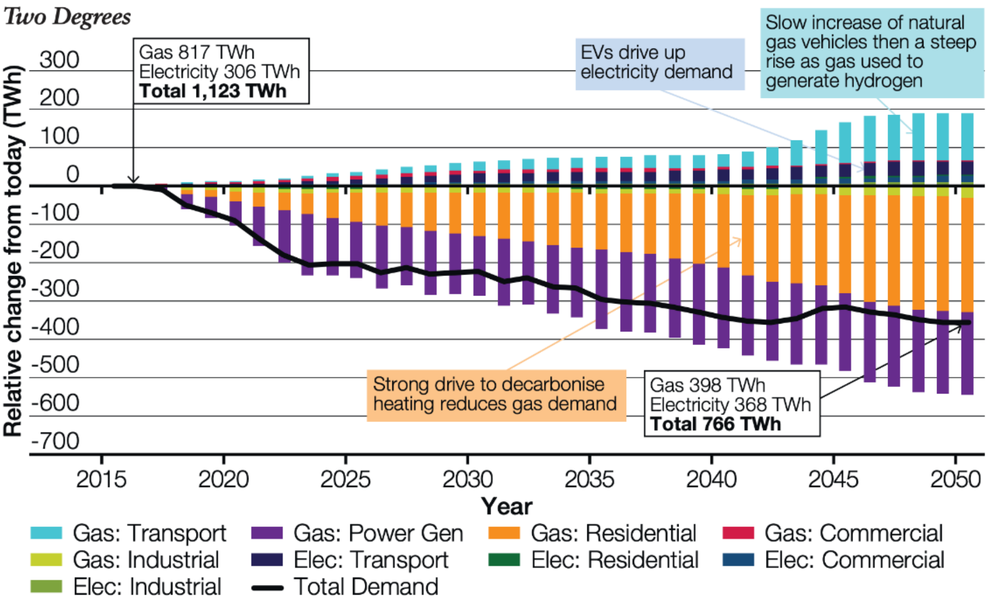

Figure 12 Gas and electricity demand forecast for the UK across all sectors [12]

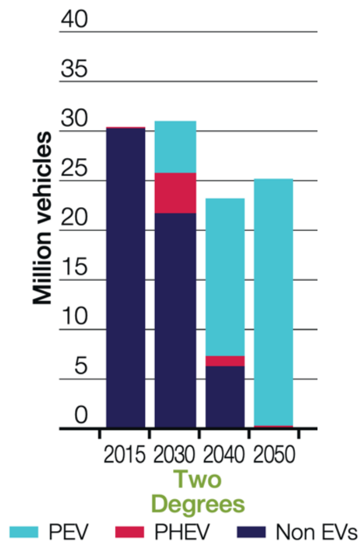

Figure 13 Electric Vehicle Forecast for the UK [12]

The balanced net zero pathway also predicts the increased electrification of the domestic sector, but a net decrease of the electricity demand by 34% in 2050 [15]. A 93% decrease in electricity carbon intensity between 2020 and 2035 is also predicted by implementing carbon removal technology such as carbon capture and storage and as such may allow natural gas to be utilized again to produce blue hydrogen, slightly decreasing electricity demand [15]. Taking all of the factors into consideration, **the electricity demand is most like going to be around 442 – 463 TWh** [16] **as forecasted by the latest Future Energy Scenarios report.**

Q3A) Concept Design of a Wind Farm

The location of the wind farm is chosen based on safety, visual, noise impacts, ease of maintenance, additional infrastructure requirements and ease of grid connection. The legal minimum distance of a 125m tall wind turbine is 2000m [17] from establishments, this was taken into consideration.

The location was chosen is: Scotland, Isle of Lewis, HS2 0DL, (58.232687222529165, -6.61277457182503). It was chosen since it is an area of high average wind speeds, as shown by Figure 14. Since it is on relatively flat land with few large obstructions nearby results in high winds speeds in any direction. Areas of natural beauty such as national parks were also avoided due to the difficulty in obtaining planning permission. The location was also chosen depending on ease of transportation of the turbines; to reduce environmental impact it was decided to reduce the number of roads that needed to be built to transport the turbines.

Connection to the grid is expected to be straightforward. Figure 16 depicts a map of the 2023 grid proposed by the Electricity System Operator's electricity ten-year statement (ETYS). A 132kV cable will run within close proximity to the proposed wind farm location and is in stage 3 of 5 of the project [18]. There is a substation 9km from the proposed site to which cables from the wind turbines should connect to. Due to the short distance, it may be more economical to use overhead cables as opposed to underground cables, which also avoids excavation and trenching in difficult land.

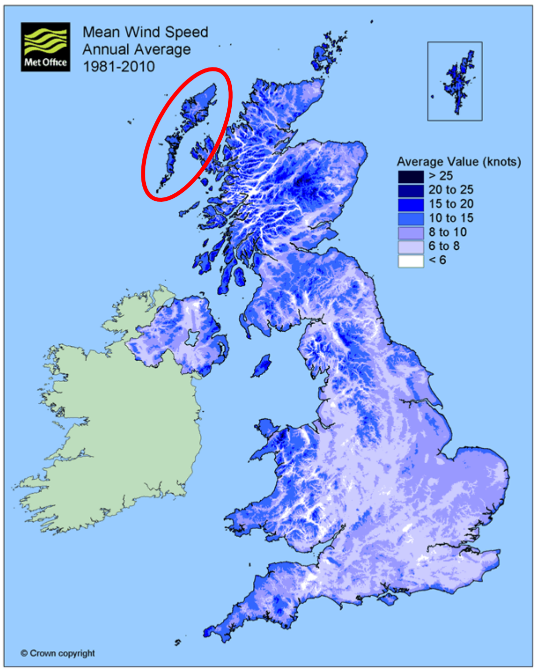

Figure 14 UK average wind speeds, red – location chosen [74]

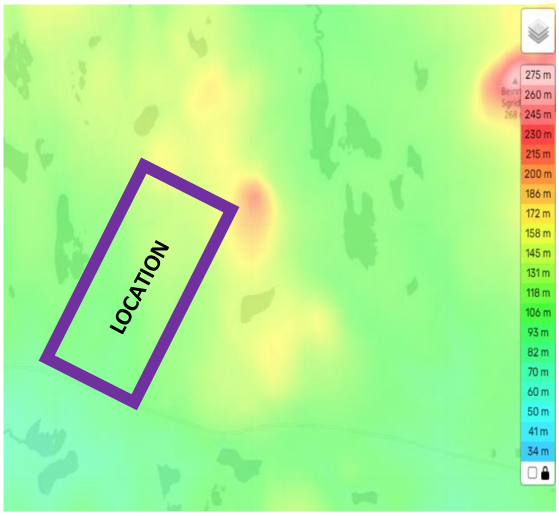

Figure 15 Elevation Map for the proposed location [75]

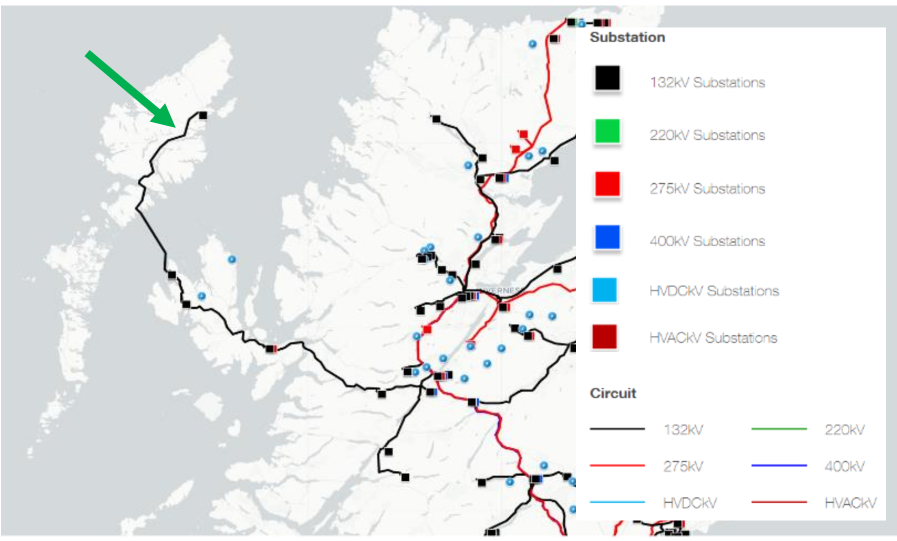

Figure 16 National Grid Map, green location shows location of plant [76]

Figure 17 depicts failures of different components of a wind turbine and the estimated hours of downtime; 1050 hours thus the wind turbines are assumed to have a reliability factor of 88%. Array losses associated with turbine wakes are assumed to be 5%, by ensuring wind turbines are positioned 5 rotor diameters apart in the crosswind direction and 8-10 rotor diameter in the predominant wind direction [19]. It is assumed that the losses during transmission are 2%, losses in the distribution network are 4%, losses in step-up/down generators and transmission/ distribution network are 2% [20] and electrical loss from the transmission to the grid is 8% [21] and so the **net losses are 33%**. It is assumed the power consumption for the weather measurement and control system is considered in the rated power of the wind turbine.

A study conducted CFD analysis to observe the efficiency of wind turbines during icing events, it was estimated there was an **8-30% power generation loss if ice was present on the blades** [22]. Ice on wind turbines can also be a safety concern since ice can fragment from the turbines and be flung over long distances potentially causing harm to people, animals or buildings [23], furthermore ice can cause load unbalances on the blades leading to fatigue failures [24].

Data recorded from the nearby Stornoway Airport shows the highest wind speeds are in the months with sub-zero temperatures and thus it wouldn't be efficient to operate the turbines in icy conditions, thus a de-icing system is recommended. Vestas's de-icing system has a rated power of 35kW [25]. 10% ice formation per month in January and December is assumed, there is a level of uncertainty since ice formation rates are location specific and very difficult to predict. It is also assumed that the de-icing system operates continuously during periods of ice formation resulting in 5.11 MWh of consumed power, this is most likely an overestimation for the energy consumption of the de-icing system.

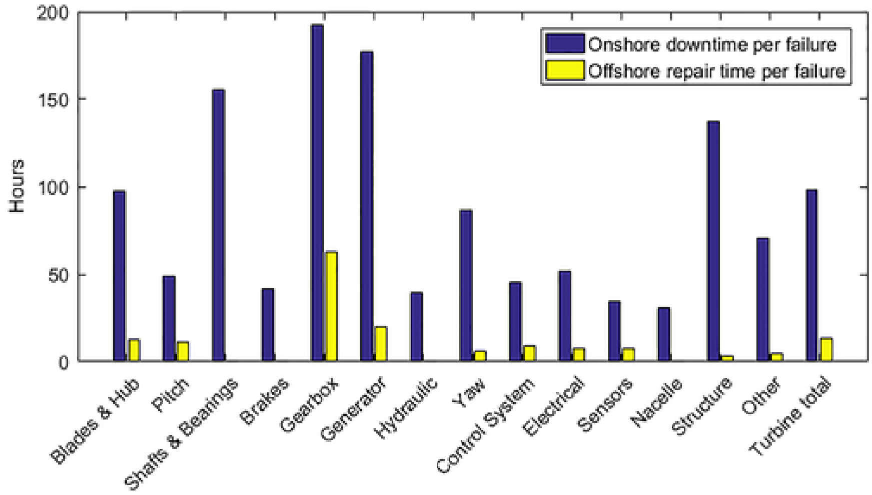

Figure 17 Failures and repair times of a wind turbine in the UK [39]

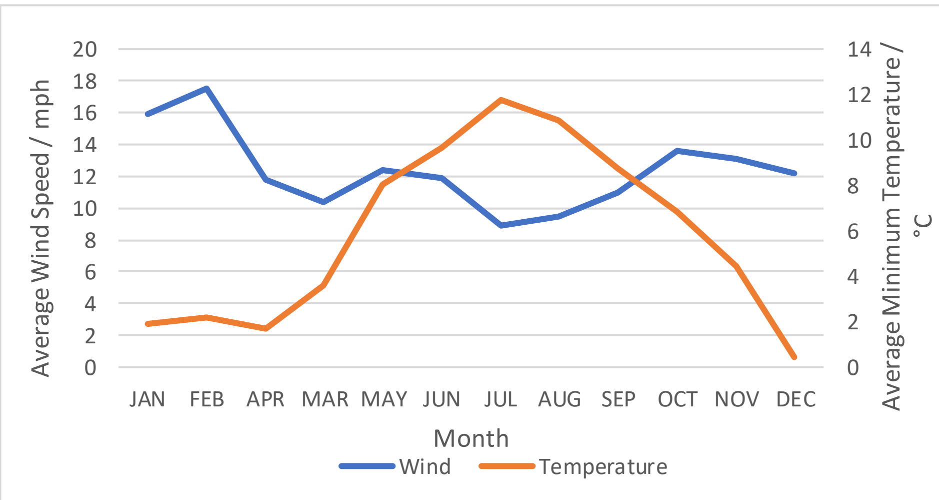

Figure 18 Weather data from Stornoway Airport [77]

The mean wind velocity at the proposed site is 6.89 m/s [26] measured 10m from the ground. This has been corrected using equation 2 to consider the height of the wind turbine and wind shear effects of the ground. A roughness length of 0.03m [27] has been chosen since the ground is relatively flat and only low-level grass and a few areas of pasture. The d factor (displacement of boundary) was assumed to be 0 since there are no obstacles nearby. The chosen wind turbine is the Vestas V112 which has a rated power of 3.45 W since the proposed wind farms' annual wind speeds fall in the operating range of the turbine, 3 – 23 m/s as seen in Figure 19 and since the visual impact isn't of paramount importance due to isolated location the upper end of the available hub height was chosen at 90m. Using equation 1 the mean wind velocity was computed at the hub height which was then used by the Rayleigh distribution to compute the number of hours per wind speed which was multiplied by the turbine output curve (Figure 20) to obtain the gross annual MWh output (Figure 21). Power losses and turbine availability were deducted from the gross annual output leading to a net output of 11166 MWh. **To meet 200 GWh/yr, 18 wind turbines are required, with a capacity factor of 36.42 %.**

$$\frac{\pi}{2}\left(\frac{V}{\bar{V}^2}\right) * \exp\left(-\frac{\pi V^2}{4\bar{V}^2}\right) where\ \ V = wind\ speed, \bar{V} = mean\ wind\ velocity - \boldsymbol{equation\ 1}\ [28]$$

$$V(h_2) = V(h_1) * \frac{\ln\left(\frac{h_2 - d}{z_0}\right)}{\ln\left(\frac{h_1 - d}{z_0}\right)}$$

$$where\ d = displacement\ of\ boundary, z_0 = roughness\ length, h = height - \boldsymbol{equation\ 2}\ \ [28]$$

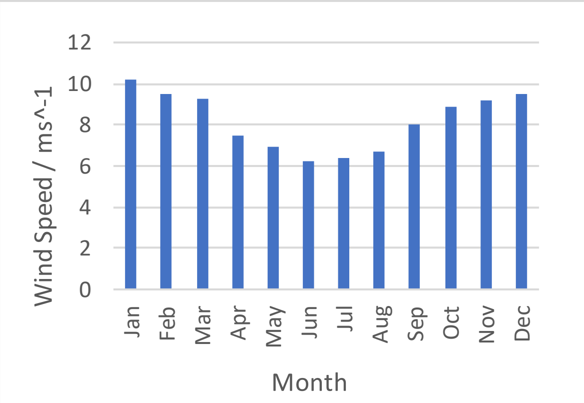

Figure 19 Mean wind velocities for proposed location at hub height [26]

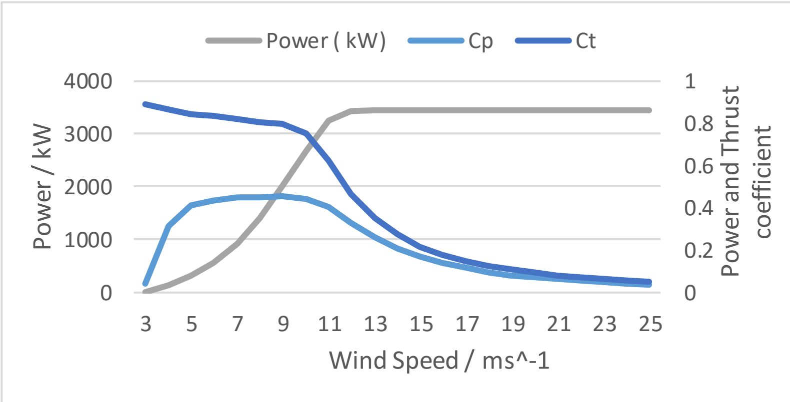

Figure 20 Power curve for wind turbine [52]

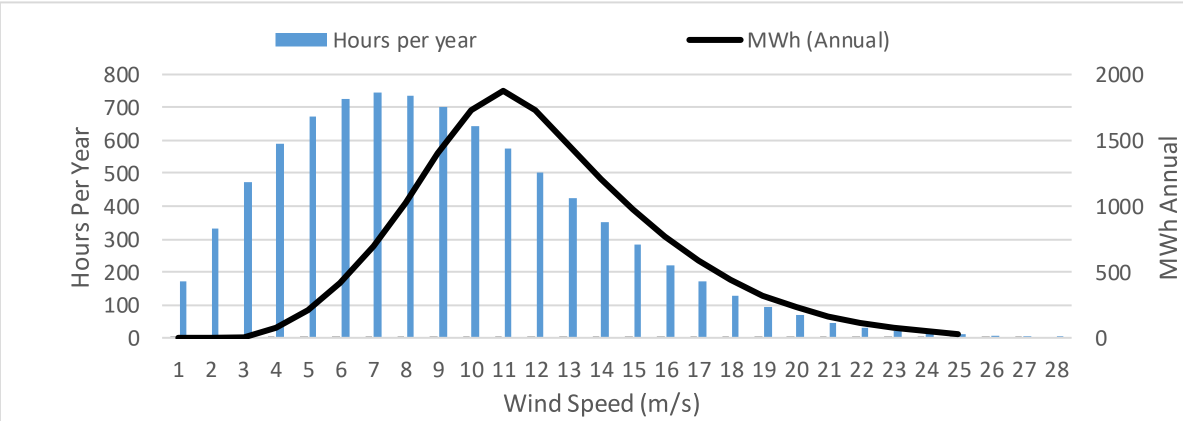

Figure 21 Rayleigh Distribution and annual MWh

Figure 22 depicts a wind rose from the Stornoway Airport which is used to assume the prevailing direction in the proposed wind farm. Figure 24 and 23 shows the direction of the prevailing wind and the recommended setup with a spacing of 5 times the rotor diameter in the cross-wind direction and 8 rotor diameters in the prevailing wind direction. The total area required is 5 square km.

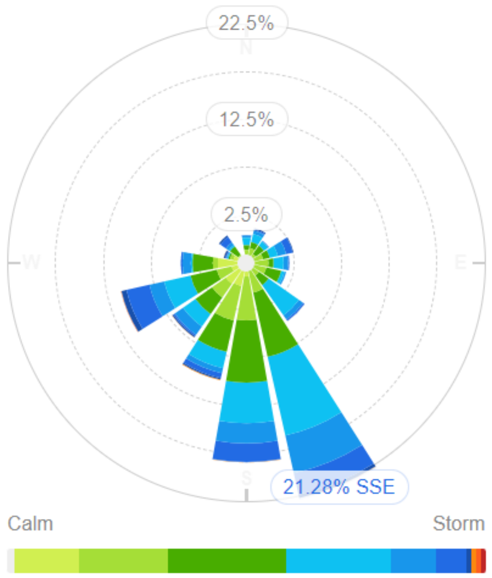

Figure 22 Windrose for the proposed location [70]

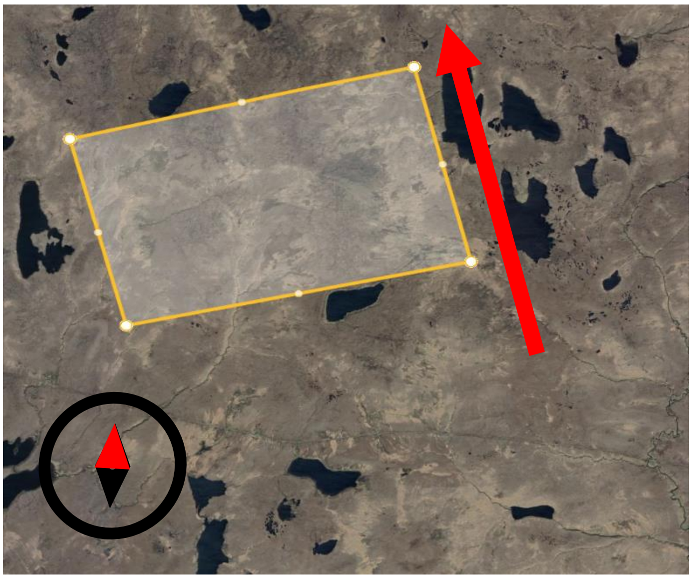

Figure 24 Satellite Image of proposed location, prevailing wind direction – red arrow [71]

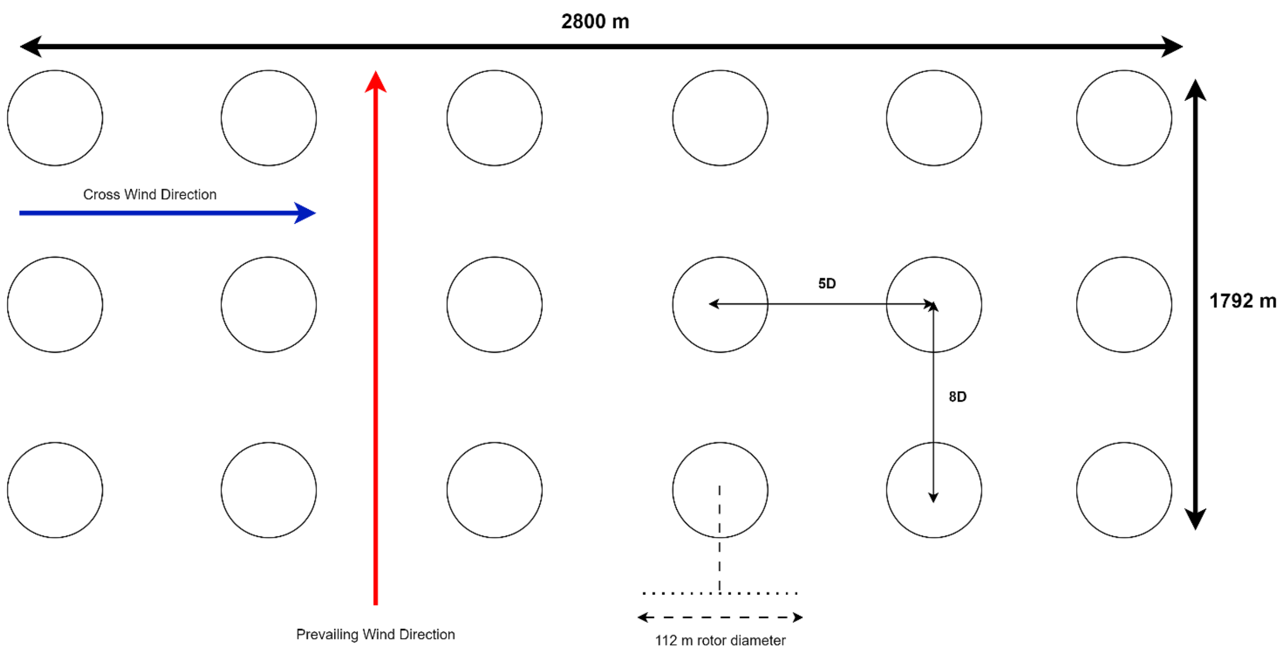

Figure 23 Wind Turbine Layout

Q3B) Solutions to intermittency

A suitable intermittency solution will consider safety, reliability, costs, and most importantly embodied emissions since that is the main reason to utilize wind energy. Energy storage technologies should have a range of discharge frequencies and discharge times to fulfil many core stationary applications such as power quality and reliability; this is represented by a large area in Figure 25, which is a study that has reviewed current energy storage costs and computed forecasts up until 2050. It can be seen in Figure 25, that there is a clear shift from mainly pumped hydro energy storage (PHES) to Lithium-ion batteries, this is linked to the increased commercialization of batteries and thus a viable intermittency solution is creating a microgrid of batteries; **Scotland is expecting to open 400MW battery storage facilities in 2024** [29] and is a good alternative to PHES since it doesn't have geographical constraints.

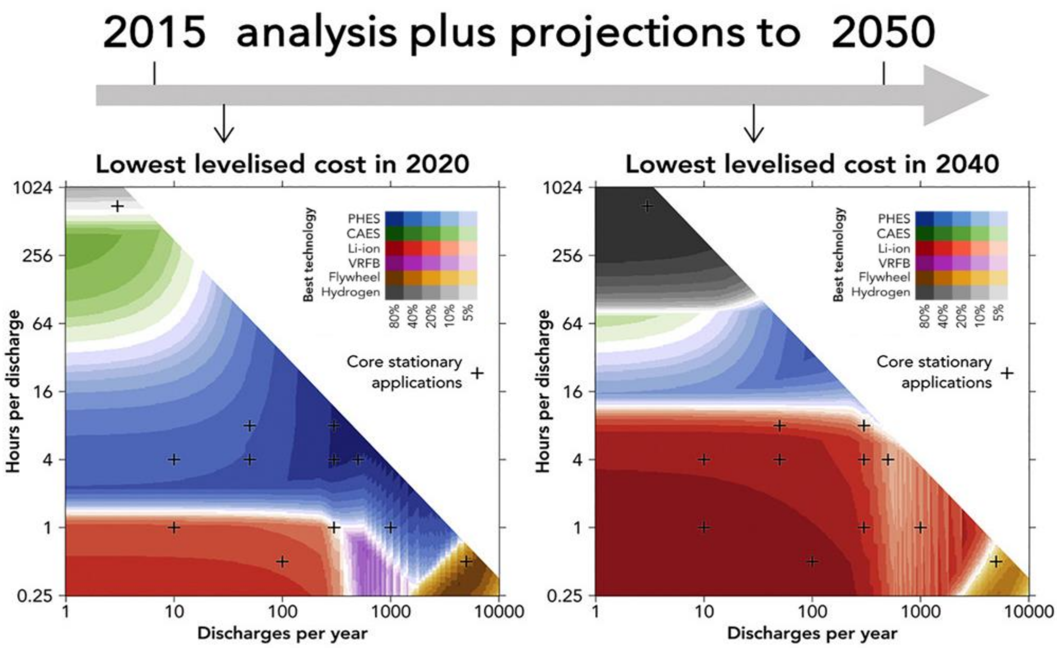

Figure 25 Levelized cost of storage for different technologies. [45]

PHES (Pumped Hydro Energy Storage), CAES (Compressed Air Energy Storage), VRFB (Vanadium Redox Flow Battery)

Hydrogen (H2) also is seen to decrease in price (Figure 25) and can be used for long discharge purposes, the UK's hydrogen demand is expected to increase and when analysing hydrogen production supply chains for different pathways, it is seen that the wind fuelled pathway has the lowest carbon emissions (Figure 26), and thus another intermittency solution is to have electrolysers connected directly to wind turbines and create hydrogen locally, which also alleviates the difficulties in transporting hydrogen since it is a low energy density fuel. This the approach taken by the **Orkney Hydrogen Strategy which stores excess energy through 2 MW electrolysers which then is passed onto a 75 kW** hydrogen fuel cell which converts the H2 into heat and power [30].

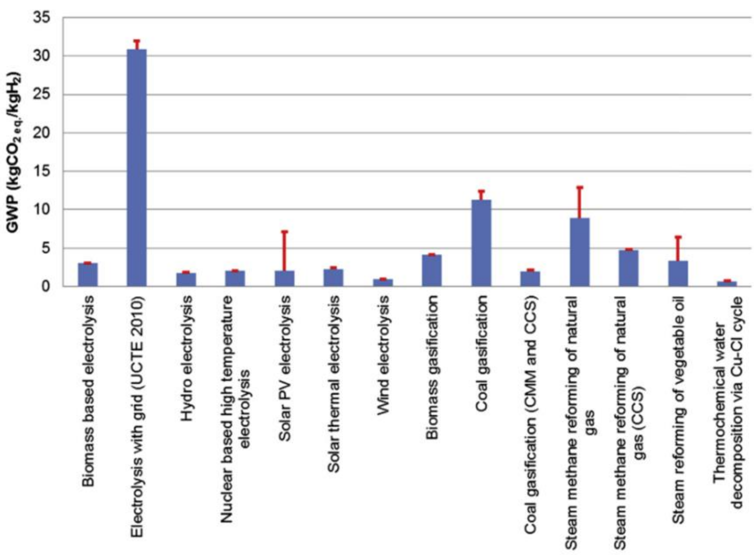

Figure 26 GWP of hydrogen production pathways [46]

Q3C) Environmental Impact

Birds can be affected by wind farms either by directly being hit by a turbine blade or when coming into contact with the transmission lines. A study looked into bird fatalities on a per kWh basis which is useful to see the future trend when there are more wind farms, the study concluded 0.4 fatalities per kWh [31] which is a large decrease relative to fatalities from fossil fuel-based processes; 5.2 fatalities per kWh [31]. This may give the impression that deaths associated with wind turbines are negligible, but this isn't the case if the species is endangered. Additionally, with the increasing importance of global warming, the number of wind turbines will increase and decrease the fossil-fuelled process which will result in a net decrease in bird fatalities.

A few mitigative approaches are to avoid migration routes [19], relocate nests to areas where wind turbines aren't present (with approval from the local environmental authority) [19], cover electrical transmission lines by funnelling them underground [19] or cover transmissions line with nonconductive materials, wind turbine shutdown in periods of extremely low visibility and times of high migration frequency [19].

Noise emitted from the turbines can be a nuisance, interfere with the health of people and potentially lead to physiological implications such as hearing loss under high noise levels and prolonged exposure [19]. Noise from wind turbines arises in an aerodynamic form which is due to the wind moving over the aerofoils, higher wind speeds tend to lead to higher noise levels. Noise in mechanical form arises from the various components (as seen in Figure 28) and its noise is amplified through the body of the turbine. Noise reduction methods are mainly associated with better wind turbine design, e.g., lower tip speed ratios and acoustic insulation inside the nacelle [19] and ensuring adequate distance between the source of noise and buildings is maintained.

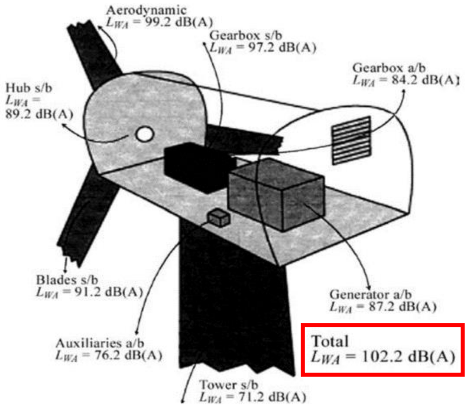

Figure 28 Mechanical noise forms, red box highlights total noise level [19]

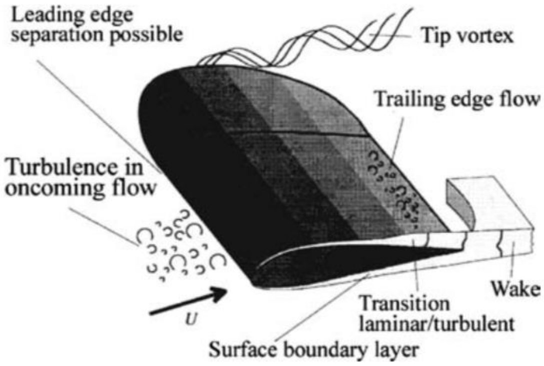

Figure 27 Aerodynamic noise sources [19]

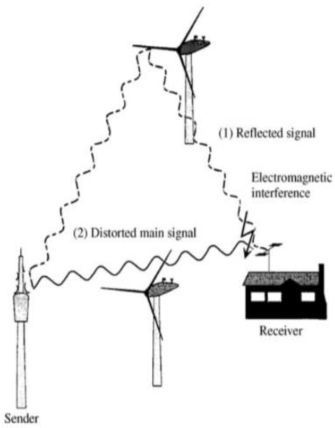

Figure 29 Electromagnetic Interference Effects [19]

Wind turbines can have **electromagnetic interference (EMI) effects** by reflecting or distorting electromagnetic waves (as seen in Figure 29), which disrupt electronic equipment. The most detrimental form of EMI are effects to aviation navigation and radar systems since they affect civilian airplanes and interfere with air defence systems [19], mitigation measures are to upgrade software of the receivers or to move the location or decrease the hub height of the wind turbine [19].

The moving blades cause an effect called **shadow flicker**, which can cast a repetitive shadow on nearby homes. Sun rays can also reflect of the high gloss surfaces (coated to be more aerodynamic), creating a flashing effect [19]. Both effects can be annoying to nearby residents and thus wind turbines should be adequately distanced to mitigate this.

Local climate temperatures have been shown to change by wind turbines. A study which analysed 8 years of satellite data and 2358 wind turbines observed a 0.724°C increase [32] occur in the near vicinity of areas near wind turbines. The local heating effect is most likely to be from the turbulence created after the wind passes an aerofoil, this can cause changes to the local climate patterns. Figure 30 depicts the results from a case study and shows the net effect of wind turbines on surface temperature changes.

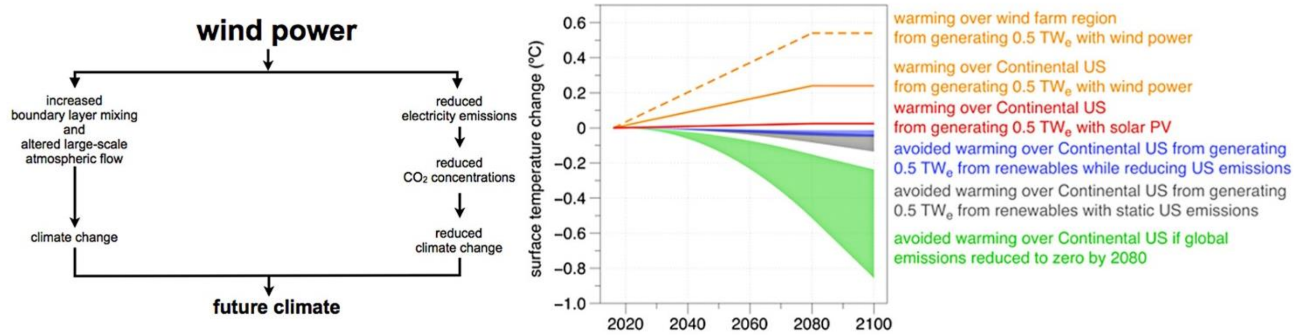

Figure 30 Local warming effects, case study in the US [49]

Rare earth elements (REE) are what constitute the magnets in wind turbines which are used to produce electricity. REE's need to be mined and in doing so can lead to permanent damage to the landscape, more importantly it can lead to severe water and air pollution. Figure 31 depicts a review which studied the possible release pathways of REE's into the environment, highlighting the widespread impacts on marine and human health.

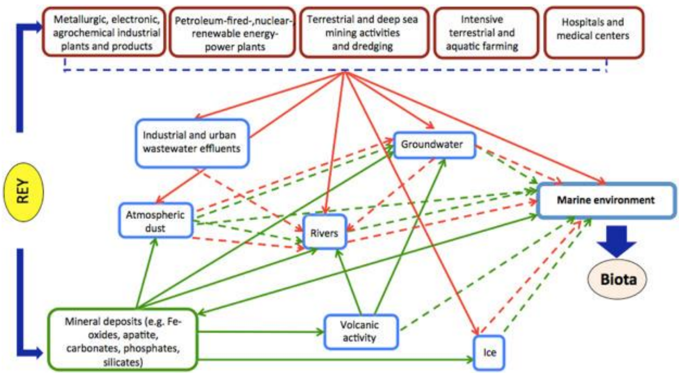

Figure 31 Deposition pathways. Indirect (dashed), Direct (solid). Red - source to marine. Green - geogenic sources [58]

Decommissioning wind turbines does have its challenges. Wind turbines are made up of composites which makes them hard to recycle due to the lack of mature, industrial scale and cost-effective solutions [33] and thus have been sent to landfill sites in large quantities.

Climate change can decrease the renewable output from wind farms. If temperatures increase in the artic this may lead to a decrease in temperature differential leading to slower wind speeds globally, the UK is expected to lose 2-3% of its output by 2050 [34]. Scientists also forecast extreme conditions which may make wind turbines inoperable. The global average surface wind speed has decreased of 0.063 m/s every decade between 1979 and 2018 [35]. On the contrary, the southern hemisphere may potentially benefit from increased wind speeds; 41% potential increase by 2100 in Australia [34].

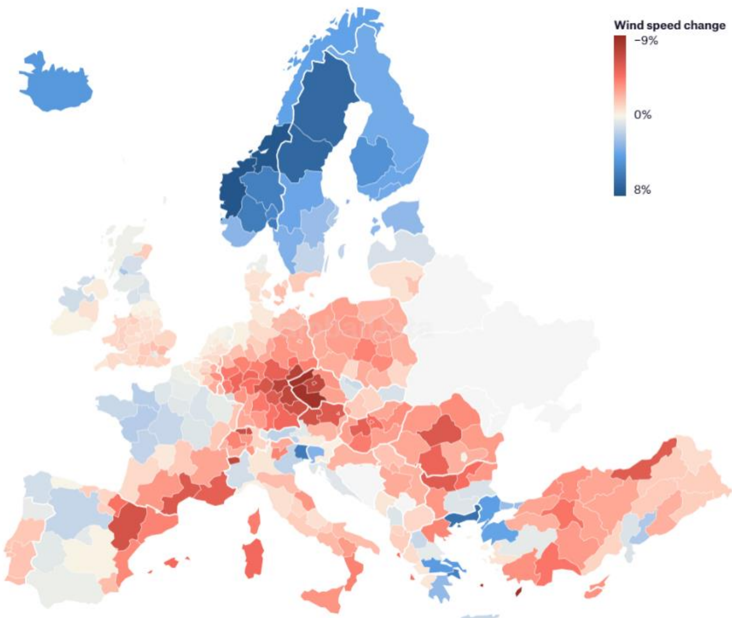

Figure 32 Wind speed changes 1979-1981 and 2018 – 2020 [72]

Q3D – Costing for the proposed wind farm

By looking at a wind turbine project with a similar location and capacity factor such as the Strathy North Wind farm, cost estimation can be conducted. Strathy North Wind Farm has a capacity of 67.65 MW and 33 wind turbines each with a rated power of 2.05MW and has a total CAPEX of £151,000,000, this cost [36] is adjusted to the number of turbines and rated power of the proposed wind farm to compute the unit costs of the wind farm which is presented in Table 1. The breakdown of the total combined DEVEX and CAPEX is shown in Figure 36. It is observed that wind turbines contribute to a large proportion of the initial investment, of which the CAPEX is broken down in Figure 34.

The land is assumed to be paid in full and expected to increase in value after 20 years due to previously installed infrastructure for a future wind farm. The tasks associated with installation are assumed to be creating access roads, excavating foundations, installing transformers, remote control, and surveillance systems, and installing cables [37]. OPEX is assumed to be £246,829 [38] per turbine, with a breakdown given shown in Figure 36. In addition to regular maintenance, it may be necessary to completely refurbish towards the later years of the wind farm to ensure the capacity factor doesn't drop and most importantly to ensure safety, and thus new equipment is acquired halfway (Year 8) through the useful lifetime of the wind farm and incurs a cost of 8% of the CAPEX costs [39], it also assumed electricity generated stays constant in-between maintenance periods. Decommissioning is assumed to mainly consist of landfill and a small proportion of recycling and thus 5% of CAPEX costs is assumed.

It is assumed the project is financed through funding available within a company thus avoiding expenses such as interest payments, but capital payments are spread out over 4 years. A windfall tax has been incorporated, which is taxed at 45% above £75/MWh of electricity generated until 2028 [40]. Additionally, corporation tax is implemented at 25% for all the operational years [41]. The electricity generated is sold at the current market average electricity price of £208/ MWh bought by non-domestic consumers as seen in Figure 33, using the average spot price wouldn't be an accurate picture due to the high volatility of prices and thus would drastically change the revenue of the company daily, a contract for difference or forward contract is assumed to be put in place to protect against this. The revenue is assumed to come from 200992 MWh/yr, the excess energy created on top of the 200 GWh/yr demand is assumed to be sold to the National Grid to be stored. A discount factor of 4% [42] is implemented since this is the current interest rate, following this equation 3 can be used to compute the levelized cost of electricity (LCOE)

$$LCOE = \frac{\sum \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum \frac{E_t}{(1+r)^t}} - Equation\ 3\ [43]$$

$$where\ I_t - investment\ cost, M_t - operational\ costs, F_t - fuel\ costs, t - time\ of\ discounting\ (yearly),$$
$$r - discount\ rate, E - electricity\ generated$$

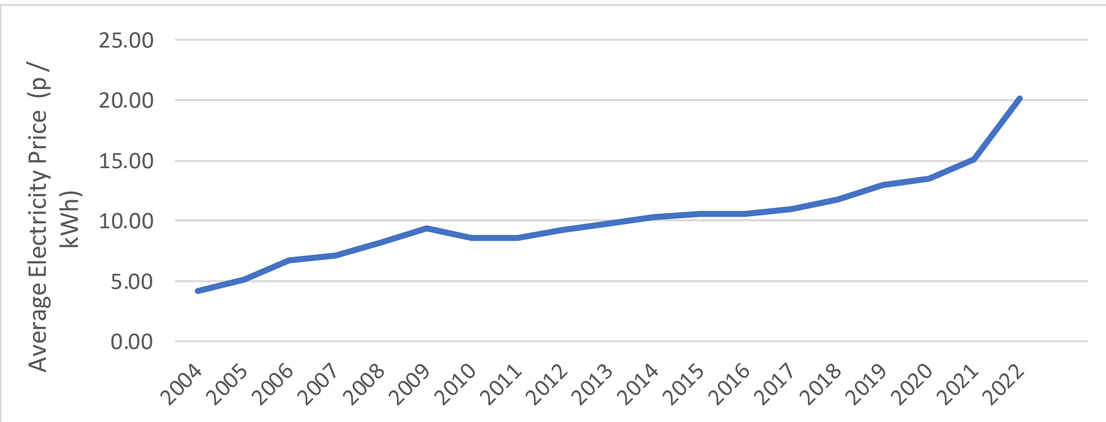

Figure 33 Average electricity price bought by non-domestic consumers in the UK, including windfall tax [73]

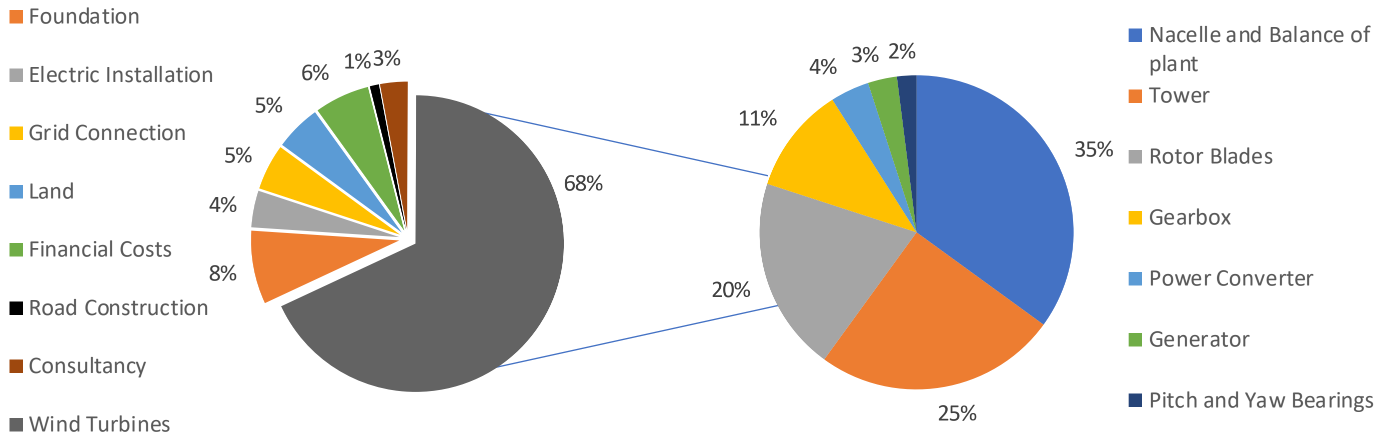

Figure 35 Percentage of capital cost per main cost driver [19]

Figure 34 Percentage of capital cost per component in Wind Turbine [55]

Table 1 Cost per unit [19] [38] [36]

Item	Unit Cost (£ /MW)
Total CAPEX Breakdown	
Wind Turbines	£1,017,772.13
Foundation	£119,737.90
Electric Installation	£59,868.95
Grid Connection	£74,836.19
Land	£74,836.19
Financial Costs	£89,803.42
Road Construction	£14,967.24
Consultancy	£44,901.71
CAPEX of Turbine	
Nacelle and Balance of plant	£356,220.25
Tower	£254,443.03
Rotor Blades	£203,554.43
Gearbox	£111,954.93
Power Converter	£40,710.89
Generator	£30,533.16
Pitch and Yaw Bearings	£20,355.44
OPEX	
Labour	£31,029.97
Parts	£24,682.93
Operations	£8,462.72
Equipment	£3,526.13
Facilities	£2,820.91
Decommissioning	£269,410.27
Refurbishment	£1,465,591.87

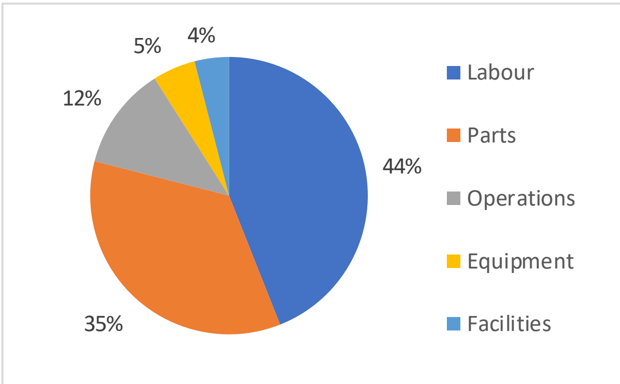

Figure 36 Percentage of OPEX [19]

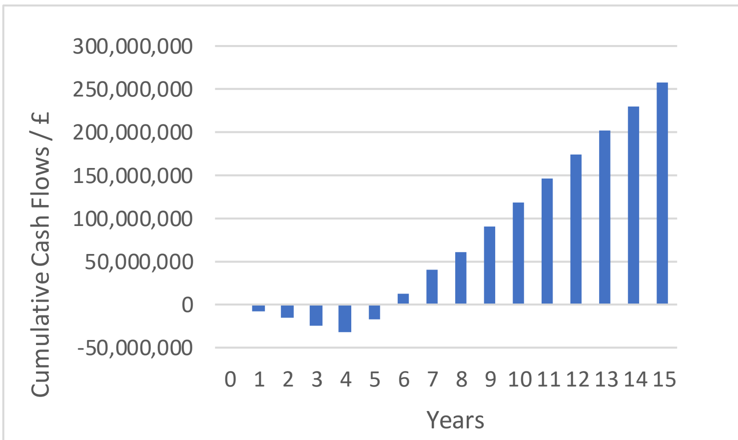

Figure 37 Cashflows for the lifetime of the project

The total revenue accumulated over the years is £627 million, total OPEX £167 million, total corporate tax £156 million, and total windfall tax £60 million. The breakeven point of the project is in the 6th year and the payback period to repay the initial investment of £94,000,000 is 10 years. **The LCOE of the electricity generated is £0.055 / kWh,** but this is expected to be even lower since the projections are only for a 15-year life span, but actual wind farms operate for 25+ years but it is still a competitive price. The net profit after tax at the end of the useful life span is £148,870,864.

Works Cited

[1] "British," 27 01 2020. [Online]. Available: https://www.ucl.ac.uk/news/2020/jan/british-carbon-tax-leads-93-drop-coal-fired-electricity. [Accessed 02 2023].

[2] N. Thomas, "How Britain ended its coal addiction," Financial Times, 1 10 2019. [Online]. Available: https://www.ft.com/content/a05d1dd4-dddd-11e9-9743-db5a370481bc. [Accessed 23 02 2023].

[3] Trading Economics - Commodity, "UK Natural Gas," 2023. [Online]. Available: https://tradingeconomics.com/commodity/uk-natural-gas. [Accessed 15 02 2023].

[4] Andrew Herring, "Hydrogen in the UK: Challenges of a clean hydrogen strategy," Marsh, 04 02 2022. [Online]. Available: https://www.marsh.com/uk/industries/energy-and-power/insights/hydrogen-in-uk-challenges-of-clean-hydrogen-strategy.html. [Accessed 13 02 2023].

[5] C. Varney, "Hydrogen East," 30 11 2020. [Online]. Available: https://hydrogeneast.uk/green-hydrogen-costs-must-fall-over-50-to-be-viable/. [Accessed 13 02 2023].

[6] University of Manchester, "Turning agricultural waste into clean energy," [Online]. Available: https://www.manchester.ac.uk/research/beacons/breakthroughs/renewable-biomass/. [Accessed 14 02 2023].

[7] Statista, "Number of sites generating electricity from hydropower in the United Kingdom (UK) from 2003 to 2021," 09 2022. [Online]. Available: https://www.statista.com/statistics/518390/uk-hydro-energy-sites/. [Accessed 01 03 2023].

[8] Department for Business, Energy & Industrial Strategy and Environment Agency, "Harnessing hydroelectric power," gov.uk, 22 01 2013. [Online]. Available: https://www.gov.uk/guidance/harnessing-hydroelectric-power. [Accessed 19 02 2023].

[9] IRENA, "RENEWABLE POWER GENERATION COSTS IN 2021," 22 09 2022. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Power_Generation_Costs_2021.pdf?rev=34c22a4b244d434da0accde7de7c73d8. [Accessed 25 02 2023].

[10] S. Evans, "Wind and solar are 30-50% cheaper than thought, admits UK government," Carbon Brief, 27 08 2020. [Online]. Available: https://www.carbonbrief.org/wind-and-solar-are-30-50-cheaper-than-thought-admits-uk-government/. [Accessed 27 02 2023].

[11] A. Siegel, "Solar Power Technologies that rocked it in 2022," Rated Power, 14 11 2022. [Online]. Available: https://ratedpower.com/blog/solar-power-technology/. [Accessed 28 02 2023].

[12] National Grid, "Future Energy Scenarios," 07 2017. [Online]. Available: https://www.nationalgrid.com/document/138976/download. [Accessed 01 03 2023].

[13] Department for Transport, Office for Low Emission Vehicles, Department for Business, Energy & Industrial Strategy, , "Government takes historic step towards net-zero with end of sale of new petrol and diesel cars by 2030," 18 11 2020. [Online]. Available: https://www.gov.uk/government/news/government-takes-historic-step-towards-net-zero-with-end-of-sale-of-new-petrol-and-diesel-cars-by-2030. [Accessed 01 03 2023].

[14] N. g. ESO, “Future Energy Scenarios,” 07 2019. [Online]. Available: https://www.nationalgrideso.com/document/170756/download. [Accessed 01 03 2023].

[15] E. Daly, “Facing the future: Net zero and the UK electricity sector,” Mckinsey, 10 02 2022. [Online]. Available: https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/facing-the-future-net-zero-and-the-uk-electricity-sector. [Accessed 01 03 2023].

[16] S. George, “National Grid ESO increases electricity demand forecasts through to 2050,” edie, 20 07 2022. [Online]. Available: https://www.edie.net/national-grid-eso-increases-electricity-demand-forecasts-through-to-2050/?regwall=success&register=success. [Accessed 01 03 2023].

[17] C. Barclay, “Wind Farms - Distance from housing,” 25 03 2011. [Online]. Available: https://ascogfarm.com/wp-content/uploads/2020/07/SN05221.pdf. [Accessed 2023 02 14].

[18] Scottish and southern electricty network and transmission, “Harris – Stornoway 132kV OHL,” 14 02 2023. [Online]. Available: https://www.ssen-transmission.co.uk/projects/project-map/harris--stornoway-132kv-ohl/. [Accessed 14 02 2023].

[19] J. F. Manwell, WIND ENERGY EXPLAINED Theory, Design and Application Second Edition, Washington: Wiley, 2009.

[20] J. Schonek, “How big are Power line losses?,” 25 03 013. [Online]. Available: https://blog.se.com/energy-management-energy-efficiency/2013/03/25/how-big-are-power-line-losses/. [Accessed 14 02 2023].

[21] B. Szyk, “Wind Turbine Calculator,” omni calculator , 10 12 2022. [Online]. Available: https://www.omnicalculator.com/ecology/wind-turbine. [Accessed 28 02 2023].

[22] L. T. C. Montoya, “A Review on the Estimation of Power Loss Due to Icing in Wind Turbines,” Energies, 01 02 2022. [Online]. Available: https://www.mdpi.com/1996-1073/15/3/1083#. [Accessed 16 02 2023].

[23] P. Kombé, “Greensolver,” Ice throw from wind turbines – risk and mitigation, 10 01 2022. [Online]. Available: https://greensolver.net/ice-throw-from-wind-turbines/. [Accessed 18 02 2023].

[24] R. Davey, “Estimating the Power Loss in Wind Turbines Due to Adverse Weather,” Azo Materials , 2 02 2022. [Online]. Available: https://www.azom.com/news.aspx?newsID=58100#:~:text=Annual%20performance%20losses%20from%20the,production%20in%20these%20weather%20conditions.. [Accessed 12 02 2023].

[25] D. A. Stökl, “Evaluation of the Vestas De-Icing System,” energiewerkstatt, 28 02 2019. [Online]. Available: https://www.energiewerkstatt.org/wp/wp-content/uploads/2019/03/Evaluation-Vestas-De-Icing-System-final.pdf. [Accessed 18 02 2023].

[26] RenSMART Limited, “RenSMART - The Renewable Energy Information Source,” [Online]. Available: https://www.rensmart.com/RenSMARTWindReport?#report. [Accessed 13 02 2023].

[27] Danish Wind Industry Association, [Online]. Available: https://web.archive.org/web/20090606011055/http://www.windpower.org/en/stat/unitsw.htm#roughness. [Accessed 17 02 2023].

[28] R. B. a. D. Y. Liu, “Wind energy notes,” UCL, 13 01 2022. [Online]. Available: https://ucl-eu-west-2-moodle-sitedata.s3.eu-west-

2.amazonaws.com/1f/e5/1fe558841dbdff56e352533df7bfc50c7ca63a17?response-content-disposition=inline%3B%20filename%3D%22Wind%20energy%20notes%202022%2013_01_22.pdf%22&response-content-type=application%2Fpdf&X. [Accessed 19 02 2023].

[29] P. A. Walker, “insider,” 25 01 2022. [Online]. Available: https://www.insider.co.uk/news/europes-largest-battery-storage-facilities-26044057. [Accessed 17 02 2023].

[30] Green Hysland , “BIG HIT,” Building Innovative Green Hydrogen systems in an Isolated Territory is an innovative €10.9 million EU supported hydrogen project hosted on the Orkney Islands of Scotland., [Online]. Available: https://greenhysland.eu/h2hub/big-hit/. [Accessed 16 02 2023].

[31] B. K. Sovacool, “Avian mortality from wind power, fossil-fuel, and nuclear electricity by Benjamin K. Sovacool,” 13 09 2009. [Online]. Available: https://www.evwind.es/2009/09/13/avian-mortality-from-wind-power-fossil-fuel-and-nuclear-electricity-by-benjamin-k-sovacool/1236. [Accessed 19 02 2023].

[32] T. M. Letcher, Wind Energy Engineering - A handbook for Onshore and Offshore Wind turbines, Acaemic Press, 2017.

[33] Wind Europe, “Wind industry calls for Europe-wide ban on landfilling turbine blades,” 16 06 2021. [Online]. Available: https://windeurope.org/newsroom/press-releases/wind-industry-calls-for-europe-wide-ban-on-landfilling-turbine-blades/. [Accessed 28 02 2023].

[34] D. DUNNE, “Carbon Brief,” 11 12 2017. [Online]. Available: https://www.carbonbrief.org/uk-wind-power-potential-could-fall-2100-because-climate-change/. [Accessed 25 02 2023].

[35] I. v. Halm, “Weekly data: Changes in wind speed caused by climate change may affect future wind power output,” Energy Monitor, 22 11 2021. [Online]. Available: https://www.energymonitor.ai/finance/risk-management/weekly-data-changes-in-wind-speed-caused-by-climate-change-may-affect-future-wind-power-output/. [Accessed 05 02 2023].

[36] Carmen, “Power Technology,” 5 Jan 2022. [Online]. Available: https://www.power-technology.com/marketdata/strathy-north-uk/. [Accessed 14 02 2023].

[37] D. w. i. association, “Installation costs for wind turbines,” [Online]. Available: http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/econ/install.htm. [Accessed 19 02 2023].

[38] Biggae Economics, “Economic Analysis of Strathy North Wind Farm,” 27 01 2020. [Online]. Available: https://www.sse.com/media/xi2kjqwc/economic-analysis-of-strathy-north-wind-farm.pdf. [Accessed 14 02 2023].

[39] C. Da0, “Wind turbine reliability data review and impacts on levelised cost of energy,” Wiley, 10 09 2019. [Online]. Available: https://onlinelibrary.wiley.com/doi/full/10.1002/we.2404. [Accessed 07 02 2023].

[40] renews.biz, “UK to impose 45% windfall tax on renewables generators,” 17 11 2022. [Online]. Available: https://renews.biz/81887/uk-to-impose-45-windfall-tax-on-renewable-generators/. [Accessed 26 02 2023].

[41] PWC, “Corporate - Taxes on corporate income,” 18 12 2022. [Online]. Available: https://taxsummaries.pwc.com/united-kingdom/corporate/taxes-on-corporate-

income#:~:text=The%20normal%20rate%20of%20corporation,do%20not%20exceed%20GBP%2050%2C000.. [Accessed 20 02 2023].

[42] Bank of England, “Interest rates and Bank Rate,” 15 12 2022. [Online]. Available: https://www.bankofengland.co.uk/monetary-policy/the-interest-rate-bank-rate. [Accessed 14 02 2023].

[43] International Renewable Energy Agency (IRENA), “RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES,” 06 2012. [Online]. Available: https://www.irena.org/publications/2012/Jun/Renewable-Energy-Cost-Analysis---Wind-Power. [Accessed 15 02 2023].

[44] Global Energy Group, “The UK’s Largest Offshore Wind Tower Manufacturing Facility to Be Built at Port of Nigg,” [Online]. Available: https://gegroup.com/latest/nigg-offshore-wind-announcement. [Accessed 13 02 2023].

[45] O. Schmidt, “Projecting the Future Levelized Cost of Electricity Storage Technologies,” Joule, 16 01 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S254243511830583X#undfig1. [Accessed 18 02 2023].

[46] R. Bhandari, “Life cycle assessment of hydrogen production via electrolysis e a review,” Journal of Cleaner Production, 12 07 2013. [Online]. Available: https://reader.elsevier.com/reader/sd/pii/S095965261300509X?token=6AEDE159A37779388AD60CD85C4896DEEAF39F24A391D6672E5E7647F4BFBE7E68720FDEA5D01941DE0B4683ED42CEED&originRegion=eu-west-1&originCreation=20230217005554. [Accessed 11 02 2023].

[47] A. Colmenar-Santos, “Simplified Analysis of the Electric Power Losses for On-Shore Wind Farms Considering Weibull Distribution Parameters,” energies, 14 07 2014. [Online]. Available: https://www.researchgate.net/publication/286106464_Simplified_Analysis_of_the_Electric_Power_Losses_for_On-Shore_Wind_Farms_Considering_Weibull_Distribution_Parameters. [Accessed 19 02 2023].

[48] W. -. I. classes, “VTT Public WIce Atlas,” 2023. [Online]. Available: https://vtt.maps.arcgis.com/apps/instant/minimalist/index.html?appid=6d93b5e284104d54b4fb6fd36903e742. [Accessed 04 02 2023].

[49] L. M. Miller, “Climatic Impacts of Wind Power,” Joule, 18 12 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S254243511830446X. [Accessed 18 02 2023].

[50] WIceAtlas, “ICE Class Virtual Map,” Project Sites, 18 02 2023. [Online]. Available: https://vtt.maps.arcgis.com/apps/instant/minimalist/index.html?appid=6d93b5e284104d54b4fb6fd36903e742. [Accessed 18 02 2023].

[51] S. S. LaVallie, “Preliminary Assessment of potential wind energy technology on the turtle mountain band of the chippewa reservation,” Sandia National Laboratories, 29 05 2019. [Online]. Available: https://www.osti.gov/servlets/purl/1864109. [Accessed 04 02 2023].

[52] “wind-turbine-models,” [Online]. Available: https://en.wind-turbine-models.com/turbines/1247-vestas-v112-3.45#datasheet. [Accessed 20 02 2023].

[53] parliment, “Losses and leakages,” [Online]. Available: https://publications.parliament.uk/pa/cm201415/cmselect/cmenergy/386/38607.html. [Accessed 13 02 2023].

[54] P. Esteban, “Power electronics-based energy storage devices for low and high voltage applications [Part 5/8: Design],” 26 11 2020. [Online]. Available: https://www.linkedin.com/pulse/modern-energy-storage-based-devices-low-high-voltage-part-esteban-4c/. [Accessed 18 02 2023].

[55] D. J. Coultate, “Wind Power Engineering and development,” 12 03 2012. [Online]. Available: https://www.windpowerengineering.com/understanding-costs-for-large-wind-turbine-drivetrains/. [Accessed 13 02 2023].

[56] B. Szyk, “omni calculator,” 10 12 2022. [Online]. Available: https://www.omnicalculator.com/ecology/wind-turbine. [Accessed 23 02 2023].

[57] Trading Economics, “United Kingdom Electricity Price,” Trading Economics, 18 02 2023. [Online]. Available: https://tradingeconomics.com/united-kingdom/electricity-price#:~:text=Electricity%20Price%20in%20the%20United,MWh%20in%20April%20of%202020.. [Accessed 18 02 2023].

[58] S. Piarulli, “Sources, distribution and effects of rare earth elements in the marine environment: Current knowledge and research gaps,” Environmental Pollution, 15 12 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0269749121018121. [Accessed 25 02 2023].

[59] CNA, “Combatting Climate Change with Nuclear Power,” 5 July 2016. [Online]. Available: https://cna.ca/2016/07/05/combatting-climate-change-nuclear-power/. [Accessed 16 02 2023].

[60] Oil and Gas Authority, “UKCS Production Efficiency Report,” 2020. [Online]. Available: https://www.nstauthority.co.uk/benchmarking/ukcs-production-efficiency-2019/. [Accessed 16 02 2023].

[61] S. Evans, “Carbon Brief,” Analysis: UK nuclear output falls to lowest level since 1982, 07 01 2022. [Online]. Available: https://www.carbonbrief.org/analysis-uk-nuclear-output-falls-to-lowest-level-since-1982/. [Accessed 18 02 2023].

[62] A. Deaney, “Electricity interconnectors in the UK since 2010,” BEIS, 30 06 2022. [Online]. Available: https://www.google.com/url?sa=i&url=https%3A%2F%2Fassets.publishing.service.gov.uk%2Fgovernment%2Fuploads%2Fsystem%2Fuploads%2Fattachment_data%2Ffile%2F1086528%2FElectricity_interconnectors_in_the_UK_since_2010.pdf&psig=AOvVaw2eZLWf9lbxHF52gkoHqMAt&ust=16. [Accessed 14 02 2023].

[63] S. EVANS, “Carbon Breif,” 27 08 2020. [Online]. Available: https://www.carbonbrief.org/wind-and-solar-are-30-50-cheaper-than-thought-admits-uk-government/. [Accessed 19 02 2023].

[64] “Onshore and offshore wind power capacity in the United Kingdom from 2010 to 2020,” 19 02 2023. [Online]. Available: https://www.statista.com/statistics/240205/uk-onshore-and-offshore-wind-power-capacity/. [Accessed 18 01 2023].

[65] “Our World of Energy,” 31 12 2022. [Online]. Available: https://www.ourworldofenergy.com/vignettes.php?type=wind-power&id=6. [Accessed 19 02 2023].

[66] B. Alves, “Statista,” 16 02 2023. [Online]. Available: Annual average wind speed in the United Kingdom (UK) from 2001 to 2021. [Accessed 18 02 2023].

[67] Z. Shahan, “Clean Technica,” UK electricity generation share by source, 11 01 2021. [Online]. Available: https://cleantechnica.com/2021/01/11/solar-wind-power-growth-in-uk-from-2012-2020-charts/. [Accessed 23 02 2023].

[68] Department for Business, Energy & Industrial Strategy and Department for Energy Security and Net Zero, “National statistics Energy Trends: UK electricity,” gov.uk, 28 02 2023. [Online]. Available: https://www.gov.uk/government/statistics/electricity-section-5-energy-trends. [Accessed 13 02 2023].

[69] L. Ingham, “UK solar capacity growth stalls as heatwave rocks the UK,” 25 07 2019. [Online]. Available: https://www.verdict.co.uk/uk-solar-capacity/. [Accessed 19 02 2023].

[70] Willy Weather, “Stornoway Airport Wind Forecast,” [Online]. Available: https://wind.willyweather.co.uk/he/western-isles/stornoway-airport.html. [Accessed 14 02 2023].

[71] “Google Earth,” [Online]. Available: https://earth.google.com/web/@58.22807345,-6.61473212,113.77223224a,4503.01298015d,35y,29.71509585h,0t,0r. [Accessed 19 02 2023].

[72] I. v. Halm, “Weekly data: Changes in wind speed caused by climate change may affect future wind power output,” Energy Monitor, 22 11 2021. [Online]. Available: https://www.energymonitor.ai/finance/risk-management/weekly-data-changes-in-wind-speed-caused-by-climate-change-may-affect-future-wind-power-output/. [Accessed 26 02 2023].

[73] Department for Business, Energy & Industrial Strategy, “Gas and electricity prices in the non-domestic sector,” BEIS, 22 12 2022. [Online]. Available: https://www.gov.uk/government/statistical-data-sets/gas-and-electricity-prices-in-the-non-domestic-sector. [Accessed 18 02 2023].

[74] Met Office, “Where are the windiest parts of the UK?,” [Online]. Available: https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/wind/windiest-place-in-uk. [Accessed 01 03 2023].

[75] topographic maps, elevation, terrain topographic-map, “England topographic map,” [Online]. Available: https://en-gb.topographic-map.com/map-kb57/England/. [Accessed 01 03 2023].

[76] nationalgrid ESO, National Grid, [Online]. Available: https://www.nationalgrideso.com/future-energy/the-pathway-2030-holistic-network-design/interactive-map. [Accessed 25 02 2023].

[77] W. Spark, “Weather History at Stornoway Airport,” 2021. [Online]. Available: https://weatherspark.com/h/y/147702/2021/Historical-Weather-during-2021-at-Stornoway-Airport-United-Kingdom. [Accessed 13 02 2023].