



# Assessing the impact of climate change on the cost of production of green ammonia from offshore wind

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## ABSTRACT

Green ammonia has received significant interest as a zero-carbon energy vector. However, current techno-economic models used to estimate the cost of producing green ammonia only use historical weather datasets as their inputs. Climate change is beginning to have an observable impact on global weather systems, so it is therefore important to examine how resilient locations for green ammonia production will be to the effects of climate change on renewable energy resources. This work examines how the cost of producing green ammonia from offshore wind farms at four locations in the UK could change due to climate change. It uses the 1981–2000, 2021–2040 and 2061–2080 2.2 km projections under the RCP8.5 scenario from the Met Office's UK Climate Projections 2018 dataset, which were bias corrected with reference to the ERA5 reanalysis dataset. Using an islanded green ammonia production model, the achievable levelised cost of ammonia (LCOA) was evaluated at four sites taken from confirmed projects in the UK's Offshore Wind Licensing Round 4, with the achievable LCOAs found to range between 935 and 1696 USD/t. Results from the three time periods were compared to assess the impact of climate change and were benchmarked against LCOAs from conventional production pathways. At all sites, increases of between 6% and 8% of the average LCOAs were observed for the 2021–2040 and 2061–2080 scenarios respectively, with the changes found to be statistically significant through application of a two tailed T-test with a confidence level of 5%.

## 1. Introduction

The energy sector currently contributes to approximately 41% of global carbon emissions [1], and demand on the sector is set to increase with power consumption projected to more than double due to improvements in living standards and widespread electrification [2]. Renewable energy technologies offer an opportunity to meet the growing demand for power whilst enabling the sector to reach net zero emissions by 2050. Renewable energy sources are also increasingly one of the lowest cost forms of new electricity generation [3].

However, most renewable energy sources only provide an intermittent supply of electricity, so their large scale deployment must be paired with energy storage technologies to ensure secure electricity supplies. There will be significant demand for multiple levels of storage capacity and duration in the future electricity grid, ranging from grid-balancing services on the order of minutes to interseasonal storage of energy across multiple weeks and months.

Green ammonia has received significant interest as a zero-carbon energy vector, as it can be produced solely from air, water, and renewable electricity. Energy can be released from ammonia either through direct combustion or 'cracking' the molecule to release

hydrogen, which can then be used as a fuel either through combustion or directly in a fuel cell. As a chemical energy storage vector, it has the potential to store energy at a large scale and for long durations, as there is little degradation of energy stored with time (unlike the self-discharge effect observed in batteries). It also has the potential to facilitate the future international trade of low-carbon energy, due to its ease of transportation and existing transport and storage infrastructure from its key role in fertilizer production and as an industrial feedstock.

In order to assess the viability of locations for green ammonia production with on-site renewable generation ('islanded production'), techno-economic modelling is typically conducted to estimate the potential levelised cost of green ammonia. Weather data is used to develop renewable energy generation profiles, which are then used in an optimisation model to design the ammonia plant as so to minimise the total system cost. Current techno-economic models typically use historical weather datasets such as the ERA5 reanalysis produced by the European Centre for Medium-Range Weather Forecasting (ECMWF). Climate change is already starting to impact on weather systems across the globe and has been linked to an increase in the frequency of extreme weather events worldwide [4]. There is a clear gap in the literature examining how climate change could affect the production costs of green ammonia;

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this work sets out to take the first steps to address this gap.

## 2. Literature review

Scientific literature examining the impact of climate change on the production of renewable energy is relatively scarce, as noted by Gaetani et al., 2015 [5]. The Intergovernmental Panel on Climate Change also concluded in its Fifth Assessment Report that "climate change will have impacts on the size and geographic distribution of the technical potential for renewable energy sources, but research into the magnitude of these possible effects is nascent" [6]. This work aims to take the first steps to address this with regard to the production of green ammonia.

Yalew et al., 2020 analysed the results of 220 studies projecting climate impacts on energy systems globally and at the regional scale, examining impacts on both energy demand and supply [7]. The impacts on renewables were found to vary substantially between technologies and regions, with studies typically reporting unremarkable or small positive effects of climate change on solar power potentials due to changes in irradiation and temperature, whilst the findings of climate impacts on wind power potential were mixed, with diverging results across regions and between studies. Combined with the UK's strong wind energy targets, the diverging impacts on wind power motivated this work to focus on the impact of climate change on wind-based islanded green ammonia production.

Solaun and Cerdá 2019 reviewed the quantitative projections of climate change impacts on renewable energy, including wind generation [8]. The output of wind turbines is highly dependent on wind speeds, and a small change can have a substantial impact on power generation and average capacity factor (total power output over time as a percentage of rated capacity). Four threats and potential impacts on wind generation from climate change were identified: 1) changes in wind speed, 2) changes in daily or seasonal distribution of wind, 3) changes in temperature, and, 4) extreme weather events.

Hdidouan and Staffell 2017 examined the impact of climate change on the levelised cost of wind energy (LCOE) in the UK, and proposed a framework for assessing its impact. This was then demonstrated by considering the UK's wind resources to 2100 [9]. These results found decreasing LCOEs in the north of the UK and increasing LCOEs in the south, with a non-linear response of the UK's wind energy resource to increases in climate forcing. In some locations a statistically significant change was found. This work used data from CIMP5 climate models to compare the effect of three emissions scenarios (Representative Climate Pathways 4.5, 6.0 and 8.5). It also outlined the importance of validating predicted data from the climate models against historical data to remove any systematic bias present in the data; an approach followed through this work.

Solaun and Cerdá 2020 built on existing research to add an economic component to assess how climate change could affect operating margins and investment values in four onshore wind farms in Spain. These were chosen from a list of over 200 that are currently in operation [10]. The four wind farms were chosen as so to be located far from each other and in representative areas that allowed for comparison with existing literature. Results from the EURO-CORDEX climate model for two emissions scenarios (RCP4.5 and RCP8.5) were used as inputs and two 23 year periods were examined (2018–2041 and 2042–2065). The results showed a variation in production of up to 8% and changes in operating margins up to 10% due to climate change. Two locations increased in power production relative to historic production, but a decrease was observed at the other two. This makes it clear that the effect of climate change on wind energy will depend on location and climatic pathway; motivating the consideration of multiple locations and time periods in this work.

It is important to use modelling to advise placement of future wind farms to ensure that they will be resilient to the impacts of climate change, in addition to examining the impact of climate change on existing wind farms. Gao et al., 2019 studied the abundance and vari-

ability of wind power in mainland China using the RCP4.5 and RCP8.5 emissions scenarios across an ensemble of regional climate models [11]. The results show that the most abundant wind resources are located in the Tibet Plateau, Hexi Corridor, Inner Mongolia and part of the three provinces of the north-east, and that there will be slight decreases in wind resources under RCP4.5 and 8.5 of up to 3–4%. An increase of wind power variability was also projected under both emissions scenarios. However, whilst this approach does well to identify the richest regions of wind resource, a higher resolution simulation would be needed to support wind farm planning, especially in some regions where the local topography and vegetation may have significant influences on wind speed. This informed the focus of this work, which chose to use the highest resolution data available from the UKCP18 dataset.

Renewable power variability has been identified as a key cost driver for technologies and processes that are powered by renewables such as wind and solar. Armijo and Philibert 2020 examined the flexible production of green hydrogen and ammonia from solar PV and wind energy in Chile and Argentina, applying a techno-economic model to four locations to model the cost of production [12]. They highlight that most previous studies modelling the production of low-carbon chemicals do not address the issues around renewable variability, assuming either grid imports or low-cost buffer storage of hydrogen. The study finds that the four locations could soon produce green hydrogen and ammonia at almost competitive costs, with renewable power variability identified as a major cost driver.

Technologies such as green hydrogen and ammonia are receiving increased attention for their potential to decarbonise sectors that have difficulties electrifying and could fulfil roles in enabling the long-duration storage and transport of renewable energy. Salmon and Bañares-Alcántara 2021 reviewed the potential for green ammonia as an energy vector for international import and export of energy [13]. In a decarbonised future, green hydrogen is forecast to represent up to 20% of global energy use, with countries such as Japan, Germany and South Korea having already announced their intentions to import hydrogen. Green ammonia has the potential to "densify" the transport of hydrogen and to be used as the world's reserve fuel when used as an energy vector. Compared to liquid hydrogen, it has a volumetric energy density that is nearly 50% higher and, similarly, when produced from renewable energy has a carbon footprint of zero.

There is a growing body of literature on the technoeconomic modelling of green ammonia. Nayak-Luke and Bañares-Alcántara 2020 conducted a techno-economic analysis of 534 locations in 70 countries to analyse the range of achievable LCOAs produced from solar and wind energy, using 2019 cost data and cost projections to 2030. These were then benchmarked against ammonia spot prices and LCOEs from other forms of energy storage [14]. At the best location in the 2019 scenario, a LCOA of 473 USD/t was achievable, but by 2030 a LCOA of 310USD/t was found to be achievable with multiple locations below 350 USD/t. These costs would bring green ammonia to cost parity with brown ammonia in several locations by 2030, showing significant potential as an economically viable energy storage method. An area identified for future work in this paper was to relax the assumption of perfect weather forecasting, given that this is not practically achievable. Climate change may impact the reliability of forecasts by increasing unpredictability in weather systems.

Recent studies have also chosen to examine the production of green hydrogen and ammonia using offshore wind energy, with ammonia often as a potential transport vector for hydrogen. Song et al., 2021 modelled the technoeconomics of producing hydrogen from offshore wind in China and delivering it to Japan, either as liquid hydrogen, bound to a chemical carrier (e.g. toluene) or as a component of ammonia. They found that ammonia was the second cheapest delivery option (after using toluene as a chemical carrier), with Chinese offshore wind identified as having the potential to provide a cost-competitive source of green hydrogen for Japan. However, the offshore wind power generation was only calculating using a 30 year historical period (from 1990 to

2019), rather than looking forward using projections.

Other studies have examined the production of ammonia to meet the existing market demands for ammonia, rather than for it to be used solely as a hydrogen carrier. Wang et al., 2021 conducted a comprehensive techno-economic analysis for green ammonia plants, with scenarios examined for both onshore and offshore production of green ammonia [15]. Onshore production would use either high-voltage alternating current or high-voltage direct current to transmit the electricity to the production plant on land. Offshore ammonia production would instead use a pipeline network or a tanker to ship ammonia to shore at a given frequency. This work found that for plants located at sufficiently large distances from shore, cost reductions of more than 50% compared to onshore production can be achieved. Meanwhile, Morgan et al., 2017 examined the production of green ammonia from U.S. offshore wind farms, reviewing the technologies required and developing an economic model for production [16]. This model was then applied to a utility connected plant in the Gulf of Maine, which found the LCOA to be very high at 1224 USD/t. A sensitivity analysis found that the levelised cost was driven in large part by the cost of producing electricity with offshore wind. Further studies should be conducted on locations in the UK, which has a much more developed offshore wind industry than the US and has published significant targets for future capacity additions.

All work on the technoeconomics of green ammonia and hydrogen production that were identified in this work's literature search relied on historical datasets such as the ERA5 reanalysis from the European Centre for Medium Range Weather Forecasting or NASA's MERRA-2 datasets.

There is a clear gap on the use of climate projections to examine the climate resilience of potential locations for green ammonia or hydrogen production, which this work endeavours to take some initial steps to address.

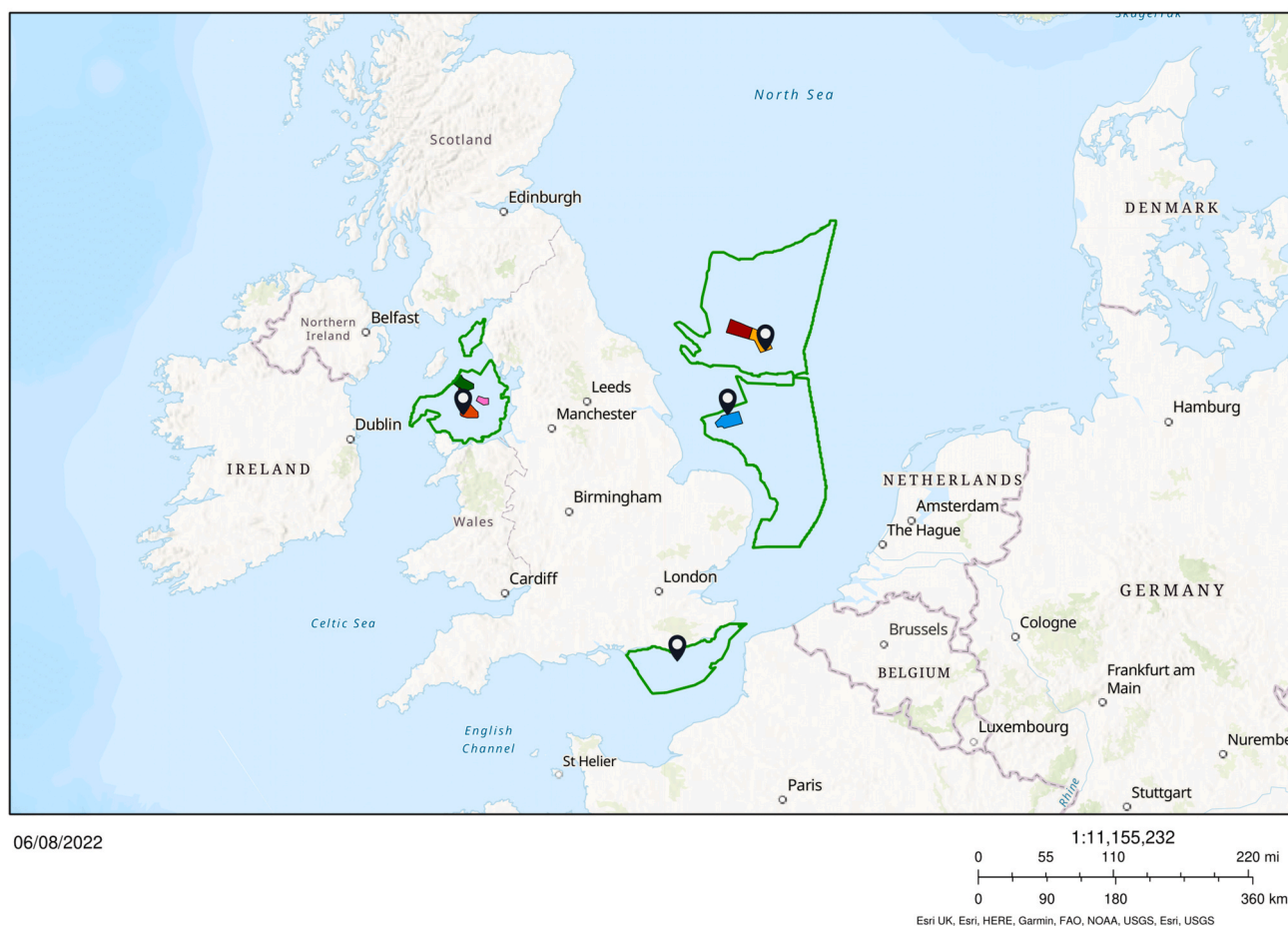
### 3. Methodology

#### 3.1. Site selection

This work examines the impact of climate change on the proposed use of four offshore wind farms for ammonia production in the UK, at the locations displayed in Fig. 1. The locations examined were taken from the four regions identified for future offshore wind developments in Round 4 of the Offshore Wind Leasing Process by the Crown Estate [17]. These six projects represent just under 8GW of new offshore wind capacity that will be in operation until at least 2050. As such they will experience the impact of climate change on their operation to a larger extent than offshore wind farms currently in operation.

Despite the clustering of projects taken forward, with five out of the six projects located in the Northern Wales & Irish Sea region and the Dogger Bank region, this work chose to select four locations within each of the Bidding Regions. This decision was taken in order to assess the spatial variability of the impacts of climate change. Modelling in this work was conducted at four geographical grid points as close as possible to the planned additions. In the case of the South East region, which has no projects, the location was selected based on proximity to existing wind farms.

#### Round 4 Locations



**Fig. 1.** Illustration of the Four Regions under identified for Round 4 of the Offshore Wind Leasing Process; pins represent the grid points at which modelling was conducted, whilst the coloured shapes indicate the locations of the six proposed projects.



### 3.2. Climate data

Climate data from the United Kingdom Climate Projections 2018 (UKCP18) was used to assess the potential impact of climate change on the availability of wind energy in these four locations. The UKCP18 are a climate analysis tool that forms part of the Met Office Hadley Centre Climate Programme. Building on the previous climate predictions (UKCP09), UKCP18 delivers a major upgrade to the range of UK climate projection tools across a range of climate scenarios.

Downscaled projections at a 2.2 km scale were selected for use, in order to accurately capture the changing dynamics of wind speed on a scale closer to the typical size of a wind farm. The UKCP18 2.2 km projections are available for the Representative Concentration Pathway 8.5 (RCP8.5), a high emission "business as usual" warming scenario.

The data is available for three time slices; 1981–2000, 20,212,040 and 2061–2080, which are the three scenarios analysed in this work. The UKCP18 2.2 km dataset has twelve different ensemble members available for use, which represent a set of plausible projections from the RCP8.5 scenario and differ due to natural climate variability and uncertainty in the climate model physics five ensemble members (01, 04, 05, 06, 07) were extracted for use in this work. To assess the accuracy of the predicted data from the Met Office's climate modelling and to provide a basis for bias correction, hourly weather data for the time period of 19,812,000 from the ERA5 dataset was extracted from the Copernicus Climate Change Service (C3S) Climate Data store. This is a fifth generation reanalysis of archived weather observations produced by the European Centre for Medium-Range Weather Forecasts. It was selected for verification purposes in this work as it is widely considered one of the most accurate datasets for modelling renewable energy, particularly wind power. Olafsson 2018 found that the ERA5 dataset showed much higher performance for modelling wind power generation when compared to measurements than the MERRA-2 dataset in all analysed aspects [18]. The ERA5 dataset for the period 1981–2000 was used to correct biases using the approach detailed in Hawkins et al., 2013 [19], which corrects both the variability and the mean of the climate model's outputs. More complex methods are available but the accuracy of bias correction must be weighed against the increased computing requirements. Bias correction was conducted on a monthly basis in order to maintain the seasonality of the data.

$$T_{BC}(t) = \overline{O_{REF}} + \frac{\sigma_{O,REF}}{\sigma_{T,REF}} (T_{RAW}(t) - \overline{T_{REF}}) \quad (1)$$

Equation (1) defines the bias correction approach used, where  $T_{REF}$  is the simulated data for the historical period,  $O_{REF}$  is the reference data for the same period, and  $T_{BC}(t)$  is the bias corrected data.  $\overline{O_{REF}}$ ,  $\overline{T_{REF}}$ ,  $\sigma_{O,REF}$ ,  $\sigma_{T,REF}$  are the means and variances of the two respective datasets for the historical period, and  $T_{RAW}(t)$  is the data for the future simulations. Equation (1) is derived from the mapping of a point between two distributions with the same shape but different means and variances. The relationship between simulations for the historical period ( $T_{REF}$ ) and the ERA5 reanalysis ( $O_{REF}$ ) is assumed to also hold for relating future simulations ( $T_{RAW}$ ) to future observations, so  $T_{BC}(t)$  is bias corrected to have the same characteristics as future observations.

### 3.3. Modelling of the cost of production of green ammonia

Following bias correction of the climate data, the data was converted into renewable energy profiles using the Vestas V90 3.0.

MW turbine's power curve. This turbine was selected as it is one of the most common turbines used for wind energy generation. Preliminary work examined the impact of modifying the wind turbine power curve on the cost of green ammonia; this was found to be negligible.

$$u = \frac{u_{ref}}{\ln\left(\frac{z_{ref}}{z_0}\right)} \ln\left(\frac{z}{z_0}\right) \quad (2)$$

The 10 m wind speeds available from the UKCP18 dataset were converted to speeds at the hub height (120 m) using Equation (2), where  $u$  is the wind speed at a height of  $z$ ,  $u_{ref}$  is the wind speed at  $z_{ref}$  and  $z_0$  is the surface roughness factor. The value of surface roughness was taken as 0.0002 for open water. Equation (2) is derived from fluid dynamics, with the scaling occurring inside the internal sub-layer of the air flowing across the land surface on which the wind turbine is located.

This work uses the green ammonia optimisation model presented in Salmon and Bañares-Alcántara 2021 [13]. It is applied at geographical grid points within the four region that are as close as possible to existing/planned wind farms. The model inputs and operation are summarised in Fig. 2- the only modifications that were made were to remove the functionality of connectivity to the electricity grid. The solar PV functionality was not used, with the model constrained to examine only wind-based production.

The model uses a linear programming algorithm to identify an optimal solution, which requires identification of a) decision variables, b) an objective function to be maximised, and c) constraints. This optimisation model was implemented in Python using the Pyomo package, and solved using the Gurobi solver, which was selected because it is one of the fastest optimizer solvers available free under an academic license.

#### 3.3.1. Capital Expenditure (CAPEX) data

Capital Expenditure (CAPEX) estimates for the equipment were taken from various sources in the literature and non-linear dependencies on the size of the equipment was removed as required by the optimisation model. Much of the equipment included in green ammonia plants has high uncertainties of cost projections, so costings were sourced from recent equipment where possible to ensure that LCOA estimates were as accurate as possible, following the methodology used in Salmon and Bañares-Alcántara 2021 [13]. Economic data used for the costing is presented in Table 1 the cost of offshore platforms and related infrastructure was not included in this modelling, as the focus was on the impact of climate scenarios.

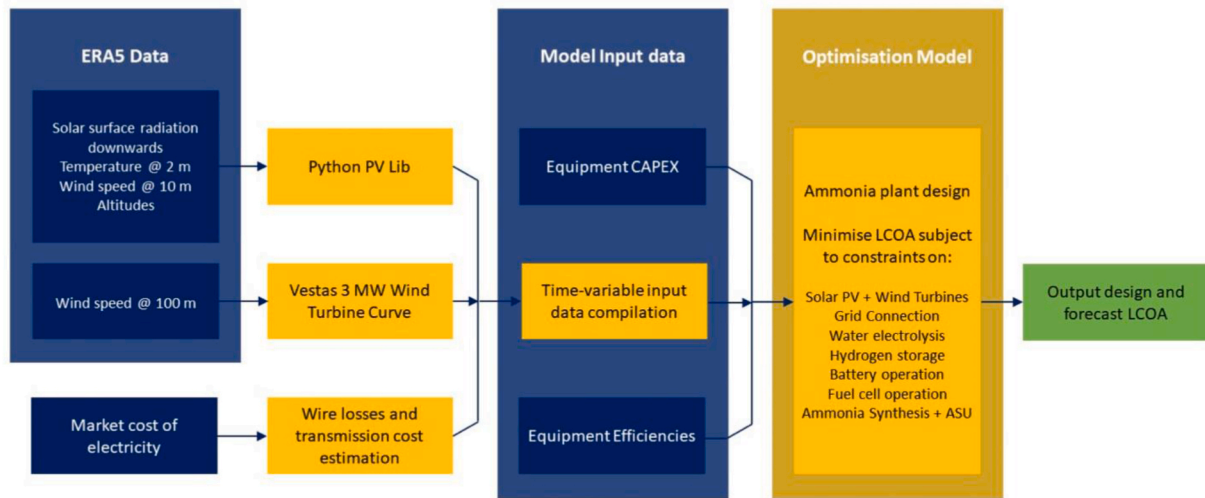
Offshore wind costs were sourced from the IRENA database (2019), which collates recent data from a large number of projects, and capital data was available for the UK offshore wind sector. Literature assumptions for electrolyzers vary significantly, with estimates typically falling between 600 and 1000 USD  $kW^{-1}$ ; this work chose to use an estimate of 700 USD  $k^{-1}$  taken from Salmon and Bañares-Alcántara 2021 [13]. A battery and hydrogen fuel cell were modelled to ensure minimum power supply to the reactor [13], with the maximum battery power/energy ratio set to 1 (i.e. minimum discharge length of 1 h), reflecting the ratio reported for selected low voltage utility scale systems [20]

#### 3.3.2. Decision variables

The decision variables are defined within six different sets; 1) the storage capacities of the components (hydrogen cell, battery), 2) renewables (wind), 3) other components (electrolyser, HaberBosch reactor and air separation unit), 4) days, 5) time, 6) flow (power from battery/fuel cell/renewables/hydrogen/ammonia). These variables are used to define the constraints, capacities and parameters of the model.

#### 3.3.3. Objective function to be minimised

The objective of the optimisation model is to minimise the levelised cost of ammonia (LCOA), which is the price at which ammonia produced would have to be sold to achieve a net present value of zero for the defined discount rate and plant lifetime. The LCOA is calculated using Equation (3), where  $CAPEX_t$ ,  $OPEX_t$  and  $m_{NH_3}$  are the capital costs, operating costs and mass of ammonia produced in year  $t$ ,  $r$  is the discount rate and  $n$  the total number of years. The discount rate was set to 7.5%, consistent with other modelling for green ammonia [13]. The plant capacity ( $m_{NH_3}$ ) has been set to 1 million tonnes per annum (TPA); this is a reflection of the typical size of an ammonia production plant.



**Fig. 2.** Schematic demonstrating the operation of the ammonia techno-economic model. Boxes in dark blue represent inputs to the model, whilst orange boxes represent processes carried out by the model. The green box is the model output [13]. In this work any electricity imports/exports from the grid were set to zero to model a fully islanded green ammonia plant. The solar PV functionality was not used in this work, with the model constrained to examine only offshore wind-based production that have been taken forward, the location was selected based on proximity to an existing wind farm. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Table 1**  
Economic Data used for CAPEX and OPEX estimates.

Parameters	Value	Units
Offshore Wind CAPEX [21]	4580	USD/kW
Haber-Bosch Reactor & ASU CAPEX [14]	7444	USD/kW
Hydrogen Storage CAPEX [14]	500	USD/t
Battery Energy Storage Component CAPEX [13]	500	USD/kWh
Battery Power Component CAPEX [13]	271	USD/kW
Electrolyser CAPEX [14]	700	USD/kW
Hydrogen Fuel Cell CAPEX [13]	960	USD/kW
Discount Rate	7.5	%
Annual OPEX Costs	2	% of CAPEX

$$LCOA = \frac{\sum_{t=1}^n \frac{CAPEX_t}{(1+r)^t} + \sum_{t=1}^n \frac{OPEX_t}{(1+r)^t}}{\sum_{t=1}^n \frac{m_{NH_3}}{(1+r)^t}} \quad (3)$$

### 3.3.4. Constraints

There are nine constraints applied within this model, which can be split into a) balance constraints and b) capacity constraints. Balance constraints enforce energy and mass conservation around the units in the chemical plant, while capacity constraints ensure that the equipment within the chemical plant is sufficiently large to handle the power and material flows that they receive.

### 3.4. Capacity constraints

1. Each component is larger than the total power provided to or delivered by it at all times.
2. For each storage component, the capacity available for storage is large enough to contain the capacity demanded by the model at that time.
3. Power provided by the battery is less than its rated power.
4. Power provided by the fuel cell is less than its rated power.
5. Accounting for the limited flexibility of the Haber-Bosch process; a minimum power requirement is enforced, as a percentage of the rated operation per hour (20%).
6. Accounting for the limited flexibility of the Haber-Bosch process; maximum rates are imposed on the ramp-down and ramp-up of the

ammonia plant production as a fraction of its rated operation per hour (20% and 2% respectively).

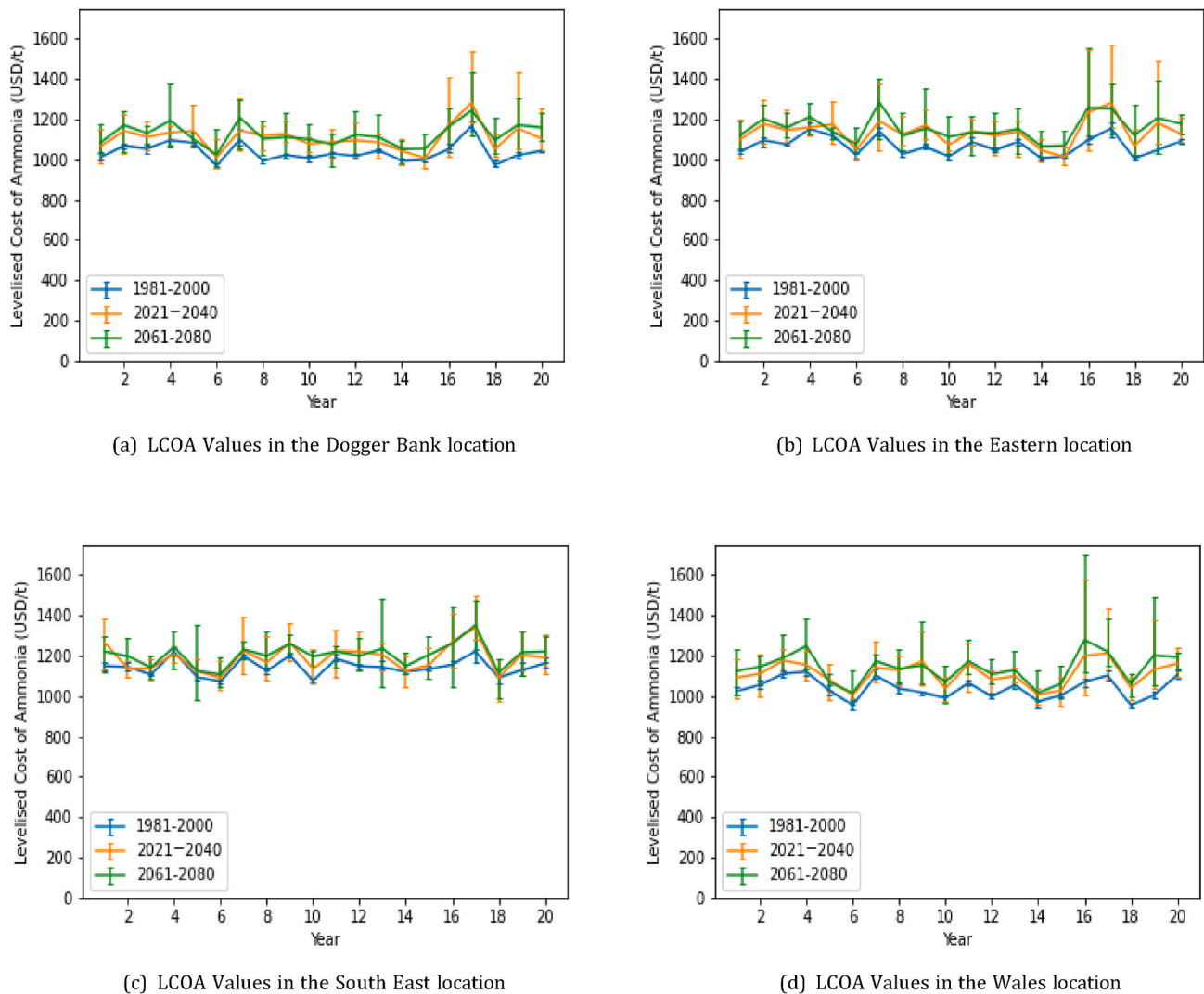
### 3.5. Balance constraints

1. The sum of all ammonia produced must equal the target production, accounting for some time off due to maintenance.
2. Total input power (from the renewables minus curtailment) must be equal to the total power to each of the components.
3. The energy stored at time  $t$  in the battery is given by the storage in the previous time step, plus the net flow in/out.
4. The energy stored at time  $t$  in the fuel cell is given by the storage in the previous time step, plus the net flow in/out.

## 4. Results

The results at the four locations compared across the three time periods are shown in Fig. 3, with the average levelised cost of ammonia (LCOA) computed for each year across the five UKCP18 ensembles in the time period. Error bars are used to represent the range of results found by across the five ensemble members. The achievable LCOAs ranged between 935 and 1697 USD/t, in a similar range to estimates from the literature for offshore based production of green ammonia [16]. An increase in both the mean and the standard deviation of the yearly LCOAs across the twenty year period was observed across all four locations for both the 2021–2040 and 2061–2080 period (relative to 1981–2000). The rise in the mean LCOH is slightly larger for the 2061–2080 period, and in almost all cases there is a greater variance in the LCOH for 2061–2080 than for 2021–2040.

In all locations the wind generation capacity is largest in the 2061–2080 period, an average of 4.67% higher than for 19,812,000. Across all four locations the wind capacity is also higher in 2021–2040 than in 1981–2000, with an average increase of 3.68% relative to the results for 1981–2000. A larger installed wind capacity is required to produce 1 m TPA of ammonia, suggesting that the energy resource has either fallen, its variability has risen, or a combination of the two. Analysis of the wind profiles showed that the wind energy resource had fallen slightly in both the 20,212,040 and 2061–2080 periods, with the most substantial change in the months of July, August, September and October. In the UK, there is an observed trend of a lower wind energy resource in the summer months as compared to winter, with climate



**Fig. 3.** Plots of the yearly levelised cost of ammonia (LCOA), measured in USD/t and compared for the three time slices of twenty years that were examined in this work. Error bars represent the range of results across the five UKCP18 ensemble members used as inputs to the model in this work.

change exacerbating this difference. The lower load factors (LF) caused by the change in wind energy resource requires an oversizing of plant components, increasing the LCOH by requiring a larger investment. This explanation is backed up by the observed falls in the LFs of the electrolyser and HB-ASU units in all locations, with the average falling from 66% and 72% in 1981–2000 by an average of 3% and 1.5% for 2041–2060 and 4% and 4% and 2.4% for 2061–2080 respectively.

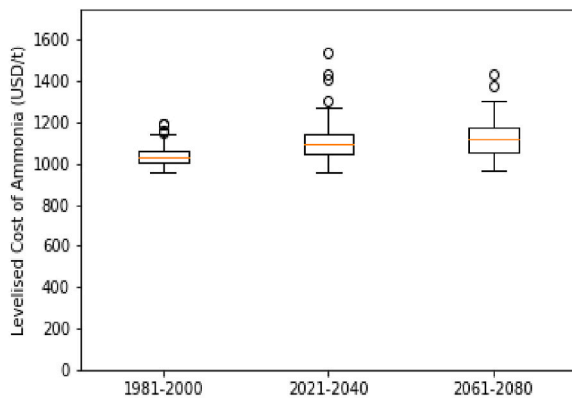
Comparison of the distributions of the LCOAs found across all of the ensemble members are shown in Fig. 4. There is a slight increase in the mean LCOA for both the 2021–2040 and 2061–2080 periods (at an average of 6.04% and 7.83% respectively compared to 1981–2000). The range of values for the yearly LCOAs has increased compared to the 1981–2000 periods, with the increase skewed towards higher LCOAs. This explains the rise in the average LCOA for the 2021–2040 and 2061–2080 periods.

Two-tailed T tests with a significance level of 5% were conducted to assess if the difference in the yearly LCOAs for the 2021–2040 and 2061–2080 time periods were statistically significant relative to the results for the 1981–2000 time period. The results are shown in Fig. 5. For all cases, the change was found to be statistically significant, with the highest P Value at 0.004% in the South East between the 2021–2040 and 1981–2000 results; a P Value below 5% is considered a statistically significant difference between two distributions.

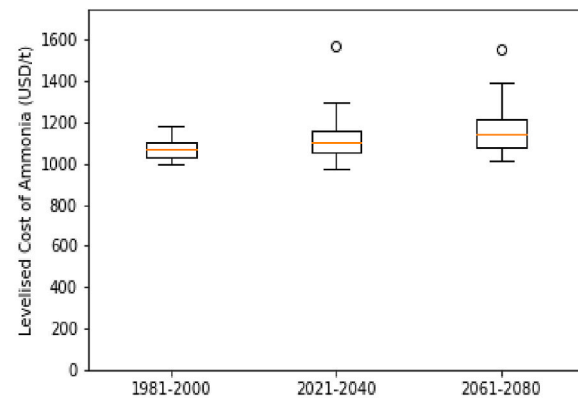
## 5. Discussion

The climate model used by the Met Office for the UKCP18 2.2 km projections is the "most comprehensive picture yet of how the climate could change" in the UK. These results strongly suggest that climate change will have a statistically significant impact on offshore wind energy resources at these four locations in the UK, and on the potential of these to be used to produce green ammonia. This is due to a change in the variability of the wind resource, as reflected by the increased wind capacity required for the 20,212,040 and 2061–2080 time periods relative to 1981–2000.

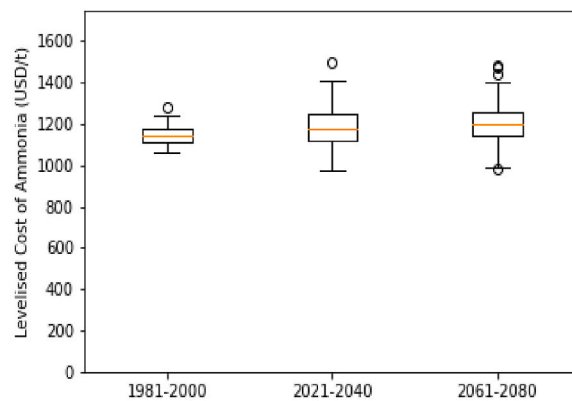
Even in the best locations (in Dogger Bank during 1981–2000 at an average of 1037USD/t) the ammonia produced will not be cost-competitive with the historic cost of producing ammonia from natural gas, which varies between 220–450USD/t [22]). These results are cheaper than the findings of Morgan et al., which found a LCOA of 1224 USD/t for offshore wind based production in the US. Comparing these costs to the cost of producing green ammonia onshore, which some estimates in the literature placed as low as 480 USD/t in 2019 in some locations [14], this is still over double the cost, mainly due to the high cost of offshore wind relative to onshore wind or solar electricity generation. Since this work was conducted, the cost of offshore wind has continued to fall and this is expected to continue over the coming



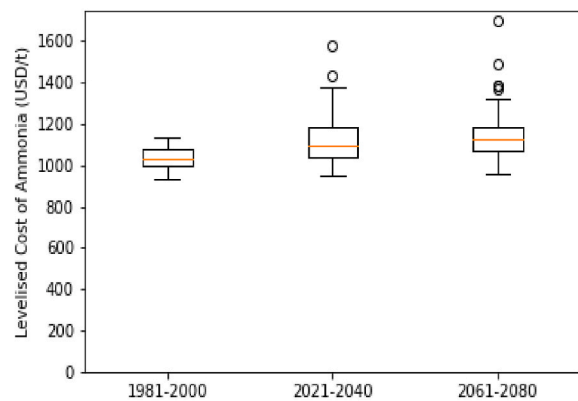
(a) Comparison of the distribution of LCOA Values in the Dogger Bank location



(b) Comparison of the distribution of LCOA Values in the Eastern location

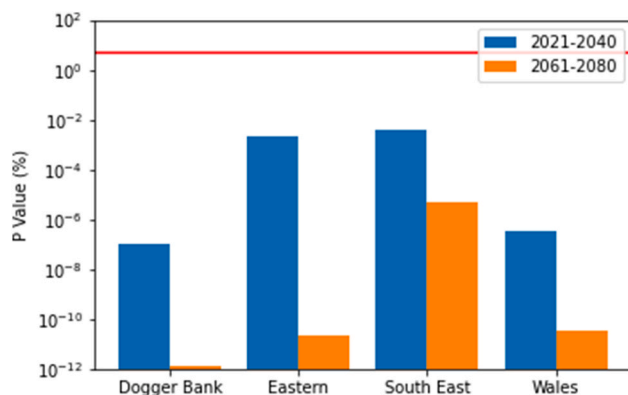


(c) Comparison of the distribution of LCOA Values in the South East location



(d) Comparison of the distribution of LCOA Values in the Northern Wales location

**Fig. 4.** Box plots of the range of distribution of the levelised cost of ammonia (LCOA) for each location, calculated using each individual year within the five ensemble members taken from the Met Office's UKCP18 dataset. The distributions are compared for the three time slices of twenty years examined in this work (1981–2000, 2021–2040, 2061–2080).



**Fig. 5.** Results of a two tailed T test comparing the range of LCOH in the 2021–2040 and 2061–2080 time periods with those from 1981 to 2000 period, with a significance level of 5% indicated by the red line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

decades[23].

However, 2022 saw a rapid increase in the cost of natural gas, driven by Russia's war in Ukraine, which pushed gas prices to increase nearly five-fold relative to their levels in early 2021 [24]. This has had a knock-on impact on many products and sectors, including food prices, and the electricity sector, but also on ammonia producers in Europe, who have had to cut their output or even halt production entirely. Fertilizer production in Europe has fallen by nearly two-thirds [25]. Ammonia cost and freight prices at Hamburg were estimated at 1645USD/t for the three months ending in June 2022, making even green ammonia produced offshore competitive against natural gas based production without requiring the support of carbon taxes.

Climate change risk must be assessed for future offshore wind projects; the Committee on Climate Change noted in its Climate Change Risk Assessment the risks of an increasingly renewables based electricity system, especially with regard to offshore wind [26]. Results from this work show that climate change will have an impact on offshore wind in the UK, strengthening the case for interseasonal energy storage in a future grid with a high renewable penetration.

However, these results must be compared with other work in the literature, as the findings vary significantly based on location, climate ensembles, and the models used. For example, JBA Consulting found that impacts of climate change on offshore wind are likely to be a



combination of both gains and losses, with projected changes in wind speed being relatively small but declining in the North Sea [27], though it was not clear what level of warming was examined. Meanwhile, Zheng et al. conducted an analysis of the climatic trends of a series of key factors for wind energy in the global oceans, including wind speed occurrence and wind power density [28]. They found a positive long term trend of wind speed occurrence and wind power density, though how far this can be extrapolated is a question for climate modelling. These findings highlight that further work should examine how the use of different climate model affects the results for offshore based ammonia production.

Climate change may also affect the ability to forecast and plan for the variability of renewable resources. Techno-economic modelling of renewable energy systems such as green hydrogen or ammonia production use multi-year series of weather data as an input; in this case for twenty years and three different scenarios. The design of the plant is then optimised so as to minimise the LCOA produced. However, in reality operators will only have a) historic data and b) climate projections, combined with a 7–10 day weather forecast with some level of reliability and accuracy. Preliminary work from the OXGATE group has found the lack of complete knowledge of the whole weather data series can increase the LCOA by up to 20 USD/t [29]. However, these preliminary calculations only used variability in historical data and did not account for the increased variability and changing seasonal distributions that climate change may cause.

This work has examined the impact that climate change will have on the LCOE and the LCOA both produced from offshore wind in the UK. However, in a future flexible UK energy system it may not make sense to have offshore wind entirely dedicated to electricity generation or to the production of clean energy vectors such as hydrogen or ammonia. There may be competition between the two uses and so it may be more economical to synthesize chemical energy carriers when the energy would otherwise be curtailed or when the electricity price is below a certain level. For example, the planned green ammonia plants of 1 m tonne per annum modelled would use up to 1300–1750 MW of capacity, a projected 3% of the UK's targeted future generation from offshore wind. Clearly, analysis of the supply and the demand sides is needed to assess the relative economics of grid-connected production compared to islanded production. Salmon and Bañares-Alcántara 2021 takes the first steps to examine this issue with an Australian focus [13]; given the significant targets for offshore wind in the UK, similar analyses would be valuable for planning the future of the UK energy system and should include the use of data from climate modelling.

## 6. Conclusions

Green hydrogen will have an important role to play in decarbonising a range of industries, and could provide a sustainable, long-duration energy storage vector that could become a globally traded commodity in the future. Ammonia, which is produced from combining hydrogen with nitrogen extracted from the air, is one of the most viable chemical stores of hydrogen ("hydrogen carriers") as it has a high hydrogen content and energy density and thus can be much more easily transported. It can either be decomposed back into hydrogen and nitrogen or directly used in power generation.

The UK has a strong offshore wind energy resource, and has published ambitious targets of 50 GW of generation capacity by 2030, enough to power every home in the UK [30]. As the grid penetration of low carbon energy and renewables increases to the recently published target of 95% by 2030, there will be a stronger need for long duration energy storage technologies such as hydrogen and ammonia to be integrated onto the electrical grid, as well as other technologies such as flexibility and demand side reduction. Government Ministers see the UK as well placed to develop a hydrogen industry based on its substantial offshore wind resource, and it could deliver up to 35% of the UK's energy supply by 2050 if net zero goals are to be realised [31].

Techno-economic modelling can be used to identify sites with particularly strong potential for green hydrogen and ammonia production. As the impacts of climate change begin to become more widespread and more extreme, including analysis of the resilience of potential sites to these impacts will be important; this could have a significant impact on the cost and operation of the chemical plant, as shown by this work. Across the four sites, the LCOA increases by an average of 6.08% to an average value of 1129 USD/t in the 2021–2040 time period, and rises by an additional 1.79% to an average of 1156 USD/t in the 2061–2080 time period. There is a clear impact of climate change on the economics of ammonia production based at these locations.

Offshore wind projects in the UK (excluding in Scotland) are awarded seabed rights through a bidding process controlled by the Crown Estate. However, existing projects are not required to evaluate the impact that climate change may have on their cost and viability. The analysis conducted by this work takes the first steps to assess the impact that climate change will have on the viability of using offshore wind for the production of green ammonia. Policy recommendations following this work are for climate resilience and risk assessments to become an integral part of the assessment and bidding process, given the observed impact of climate change on the wind energy resources and so the theoretical cost of producing ammonia at these four locations.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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