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A global, spatially granular techno-economic analysis of offshore green ammonia production[☆]

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ABSTRACT

Decarbonisation will see mass installation of wind turbines and solar panels to replace conventional energy systems. However, these renewables face two challenges: renewable energy production is intermittent, and land requirements are considerable. We propose a solution to both problems: production of green ammonia, a carbon-free fuel, in the ocean. Green ammonia can be produced from intermittent renewables, and can be dispatched as a hydrogen carrier, energy vector, shipping fuel, or decarbonised fertiliser. It is well suited to marine production — it benefits from the ocean's reliable wind resource, is easily transportable, can be stored cheaply under mild conditions, and only requires water, power and air for production. This article presents the first global heat map for ammonia production which considers ocean production, land availability restrictions, and transport to major demand centres. We show that, even considering the high costs of floating wind turbines, it is likely that cost savings will be realised by producing some of the global ammonia demand in the ocean (the precise fraction depends on the distribution of demand), predominantly because competition for land will limit onshore capacity in the best locations.

1. Introduction

Green ammonia[1] is a renewable fuel that has the capacity to play an important role in decarbonisation: it is produced from only water, power and air, and can be dispatched on demand as a fertiliser, shipping fuel, hydrogen carrier, or for back-up power supply. Increasingly, ammonia is appearing in national hydrogen strategies as an enabler of the hydrogen economy due to its superior energy density (German Federal Ministry for Economic Affairs and Energy, 2020; Government of Scotland, 2020). A large, and quickly increasing, number of projects intend to produce green ammonia in order for it to be exported as an intercontinental energy vector (Ammonia Energy Association, 2021).

In particular, compared to hydrogen, it is both more easily stored and transported. Ammonia is liquid under mild conditions relative to hydrogen (at atmospheric pressure, the boiling point for ammonia is -33 °C, compared to −253 °C for hydrogen National Institute for Standards and Technology, 2020), under which conditions it can be stored cheaply for long periods of time. There is significant infrastructure for ammonia transport via both ship and pipeline around the world (Bartels, 2008). Because it has similar properties to LPG, there is capacity to scale up transport using existing gas carriers (Salmon et al., 2021).

Given those favourable properties, ammonia can be produced in isolated locations and subsequently transported to demand sites without meaningful increases to project costs. This creates a neat synergy with the emerging floating wind turbine industry, which takes advantage of an excellent resource far offshore, but which incurs considerable costs because of the cost and efficiency losses of transmitting power over long distances (Ghigo et al., 2020). There are a number of other synergies: (i) in some locations, offshore wind produces power not only in large quantities, but also with high consistency, which is necessary in green ammonia production in order to stabilise the operation of the Haber–Bosch plant; (ii) green ammonia production needs water as a process input, which may not be available at inland facilities in large quantities, but can be produced easily by desalination at sea, and it is increasingly possible to produce hydrogen directly from sea water (Germscheidt et al., 2021); (iii) green ammonia production is not labour intensive, meaning the increased costs of operators at sea compared to on land are unlikely to be significant; (iv) because of the efficiency losses caused by conversion to hydrogen and subsequently hydrogen derivatives, production of renewable fuels may be unjustifiable in countries without large areas of free land and which must therefore use land-intensive renewable energy efficiently — such competition is likely to be negligible at sea; (v) land-use change emissions associated with installing

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[1] For the purposes of this paper, green hydrogen and ammonia are considered to be produced using renewable electricity and water electrolysis.

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renewable energy in some locations can be avoided (van de Ven et al., 2021).

To that end, several projects are emerging which will produce green hydrogen and ammonia using an offshore resource: Yara and Ørsted will produce ammonia onshore in Norway using offshore wind (Ørsted, 2021); Siemens is developing a wind turbine which integrates a floating water electrolyser (Siemens Gamesa Renewable Energy, 2021); the PosHyDon project will install a small water electrolyser on an existing oil and gas platform powered by offshore wind (PosHyDon, 2021). In the longer term, consortia in the Netherlands and Germany have both announced intentions to produce green hydrogen in the GW scale using offshore wind by 2030; some of the P2G infrastructure will be on land, but the German group has explicitly stated an intention to produce 290 MW of hydrogen on an offshore platform by 2028 (A. B. of Shipping, 2022). The Thang Long offshore wind farm in Vietnam is investigating the construction of an offshore mounted structure from which electricity, hydrogen, ammonia could be exported (Wind, 2022).

Beyond the utilisation of offshore wind, the possibility of offshore solar may also enable higher utilisation of hydrogen and ammonia production equipment. While floating solar is a rapidly growing industry, to date it has mostly been explored on inland lakes and reservoirs (Golroodbari and van Sark, 2020); however, marine applications are beginning to emerge, and they are likely to face similar transmission cost difficulties to those faced by wind turbines.

This research aims to quantify the extent to which these substantial prospective benefits of offshore production outweigh the increased costs of electricity production.

1.1. Literature review

Ammonia production onshore has been the subject of significant attention in the literature, and various authors have estimated the cost of production. Historically, many authors have produced overly simplified estimates, failing to factor in the costs of energy storage equipment, or to optimise the relative sizes of equipment (Salmon and Bañares-Alcántara, 2021a). More recently, though, an increasing number of authors have used optimisation methods which use historical, hourly weather data to design a plant that is robust to weather variability; Armijo and Philibert (2020) used this approach to estimate costs in South America. Osman et al. (2020) did the same in the Middle East, including the use of salt caverns in their modelling to reduce storage costs; and prior work from these authors produced a heat map of ammonia production costs in Australia when a grid connection to the national power market is included (Salmon and Bañares-Alcántara, 2021b). Nayak-Luke and Bañares-Alcántara (2020) considered a large number of locations (>500) and a large number of operating years (30), which was extended upon by Fasihi et al. (2021), who produced a global heat map of ammonia production onshore. This research is novel in that it extends this production analysis to offshore settings, factoring in both land availability onshore (a key driver of offshore production) as well as the unique engineering conditions offshore operation.

While a number of authors have conceptually considered production of hydrogen or one of its derivatives offshore (Patterson et al., 2019), this rarely includes conversion to green ammonia (although this may significantly reduce project costs). Babarit et al. (2018) estimated the cost of offshore hydrogen production with transport to shore on ships; however, in this initial stage analysis, they assumed a fixed cost of electricity delivered with a fixed load factor, and estimate quite high costs because of the difficulties of hydrogen transport. Loisel et al. (2015) and Singlitico et al. (2021) also consider hydrogen production from offshore wind at a location near France; however, they only produce hydrogen using curtailed electricity, meaning one key benefit of offshore production (namely, the absence of an expensive transmission line) is not achieved.

Some authors did consider ammonia in more depth: Morgan (2013) considered the onshore production of ammonia from offshore wind, and Parmar (2019) extended that analysis to offshore production, attaining flexibility through modularised reactors. However, because they did not consider the role of energy storage technologies (e.g. batteries), or the improvements in flexible operation of ammonia plants, they estimate very high costs of production. Panchal et al. (2009) considered hydrogen production using thermal gradients in the ocean; however, because this technology has yet to be used on very large scales, we do not consider it further here.

Wang et al. (2021) provide the most robust optimisation of ammonia costs considering offshore wind that is known to the authors. This analysis used a synthetic wind profile to estimate project costs, which used a ’representative day’ of electricity production from each month in a nominated year. However, as is discussed in Section 2, using representative days can oversimplify production costs and underestimate the true energy storage requirements, and indeed, that paper found very small energy and hydrogen storage equipment was required. Moreover, the synthetic profiles they considered used two average wind speeds — 7 m/s and 11 m/s; however, much higher wind speeds are observed in the actual historical weather data used in this analysis – the best site has an average wind speed of 19 m/s, and the average speed is greater than 11 m/s at about 16% of sites – indicating that the synthetic profiles neglect locations in which very cheap production may be possible.

No author to date has performed a meaningful assessment of land availability for ammonia production. While Fasihi et al. (2021) assessed global production potential, they did not consider which land would or would not be suitable for production, and how this may affect capacity.

2. Methodology

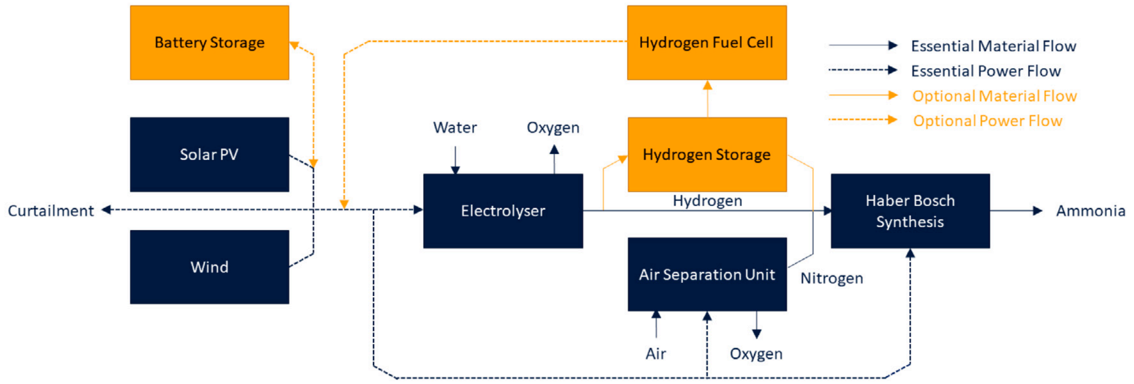
This research combines two techniques in order to obtain results. Firstly, a mixed integer linear program is used which rigorously optimises the levelised cost of ammonia production (LCOA) is applied in a grid pattern across the globe. The model takes as inputs the weather profile and the cost of equipment, and subsequently designs a plant, subject to mass and energy balances, and technological constraints, that produces ammonia at the minimum price (see Section 2.1 for a complete model description). Secondly, the actual production achievable in each location is estimated by considering the both the true land availability for renewable energy production, given other existing requirements, and the impacts of land competition with other renewable energy (see Section 2.2.1 for a description of the grounds on which land was excluded).

2.1. Optimisation approach

This paper uses a mixed integer linear programming (MILP) approach to minimise the LCOA. The Gurobi solver (Gurobi Optimization, LLC, 2022) was used to obtain results for the MILP in a grid pattern across the globe. The fundamental operation of the model is the same as that described in earlier works from the authors (Salmon and Bañares-Alcántara, 2021b). The model takes a year of hourly historical weather data from the nominated location (i.e. 8760 time periods), as well as cost and efficiency measures for wind turbines, solar panels, water electrolysers, batteries, hydrogen fuel cells, cryogenic air separation units and a Haber–Bosch process. It then selects equipment which minimises the levelised cost of ammonia for a 1 MMTPA plant, subject to mass and energy balance constraints, and technical constraints (which particularly impact the Haber–Bosch loop, since it is not as flexible as other equipment). The input parameters to the model are listed in Table S2 of the Supplementary Material, and schematic representation of the model is shown in Fig. 1.

Weather data for both onshore and offshore locations was obtained using the freely available ERA5 reanalysis dataset (European Centre for Medium-Range Weather Forecasts, 2021). However, for bathymetry data, the ETOPO Global Relief Model was used instead, since it provides more granular data to larger water depths (Amante and Eakins, 2009);

(a) - Green ammonia production



(b) - Modelling approach

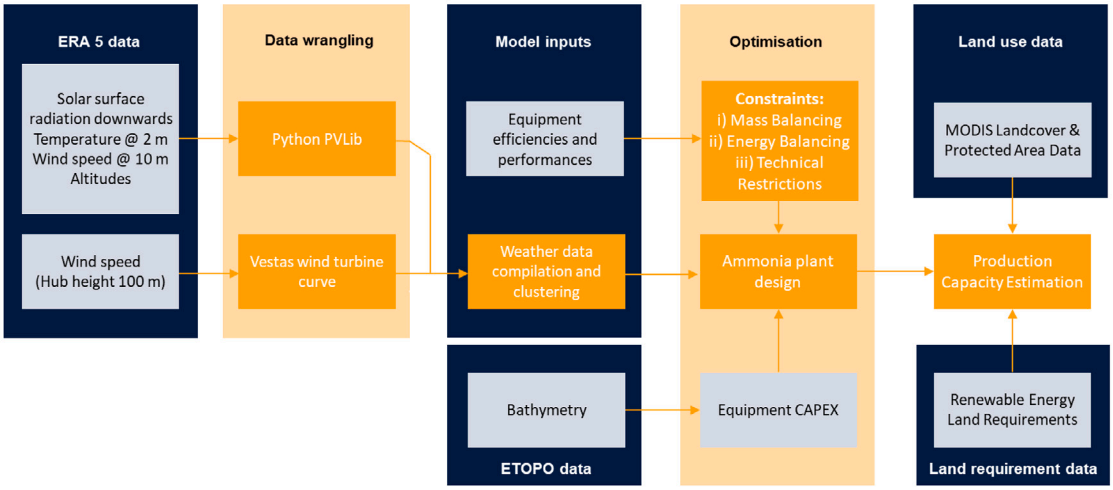


Fig. 1. Flow diagrams representing methodology. (a) — Top: a schematic diagram showing the components of green ammonia production applied in this model. (b) — Bottom: a flow diagram showing high level data sources and processing pathways.

that dataset was also used to estimate land slope for assessing the suitability of renewable energy production. Locations which were very close to the poles (i.e. latitude $< -85°$ or latitude $> 85°$) were excluded, since environmental considerations likely exclude these sites; similarly, sites in Antarctica were excluded, even if they fell within the acceptable latitude range, for the same reason.

Two major adjustments were made to the model compared to that used in earlier works: firstly, a data clustering approach was used to accelerate solution time; secondly, and more importantly, major updates were made to the cost estimations of renewable power generation to reflect the complexities of offshore conditions.

Firstly, the number of locations and scenarios considered in this analysis is very large, which means the time taken for the model to converge is significant. In order to accelerate convergence, a number of simplifications to the earlier model were investigated, using data clustering to reduce the dimensionality of the input weather data. The results are reported in another work from the authors (Salmon and Bañares-Alcántara, 2022); in which two findings were made: (i) using a 'representative day' approach, whereby a small number of relevant daily profiles are selected to represent the entire year, provides a poor estimate of system costs, because it struggles to estimate the optimal storage inventory (since the time-scale for storage during the process is large); (ii) the model can be meaningfully accelerated using time steps that are larger than one hour, with reasonable results achieved up to time steps of 8 h. For this model, a time step of four hours was used (reducing the number of time periods required to represent a full year of data from 2190 to 8760), which allows the model to converge around three times faster, with an average error of less than 2% compared to an hourly time step.

Secondly, the cost estimation in the model was updated to reflect the increased costs of offshore operation. The cost estimation for each component is discussed in the following sections. While the costs of offshore installation as a function of distance to shore and depth are considered, we do not consider here regional differences in cost (i.e. we use the same installed cost of solar panels in India and Europe, even though installed costs are much lower in India). This is because (i) it is not possible to obtain meaningful estimates of the installed costs for each country considered individually, and (ii) the purpose of this analysis is to meaningfully compare ocean and land based sites based on the quality of their resource, rather than by the local financial conditions. For that reason, costs for land based applications were taken directly from the IRENA Renewable Cost estimation report (International Renewable Energy Agency, 2021), which considers a wide range of renewable projects in their database, and reports the average and

Table 1
List of cost estimates for floating wind turbines. All costs listed are in millions of USD; where currency conversion was required to EUR, a factor of 1.12 €/USD was used, which is the approximate long term average. Where an author reported the costs of multiple technologies for floating turbines, the cheapest technology was selected for this work. Where available, present day costs are reported in preference to prospective future costs.

Author	Region	Year	Size (MW)	Turbine + Platform	Installation	Anchors	Mooring	Balance	Transmission	Cost/MW with transmission	Cost/MW without transmission
Ghigo et al. (2020)	Italy	2020	10	28	16.8	0.1	0.5	Not included	13.4	5.9	4.5
Myhr et al. (2014)	Generic	2014	1	1.8	0.34	In platform	0.6	0.28	1.1	4.1	3
The Carbon Trust (2015)	Scotland	2015	1	2.1	0.43	0.07	0.2	0.13	0.4	3.3	2.9
NREL (Stehly et al., 2020)	US	2019	1	2.7	0.48	In platform	In platform	1.1	0.98	5.3	4.3
NREL (Beiter et al., 2020)	California	2020	1	2.5	0.2	In platform	In platform	1	0.8	4.5	3.7
Katsouris and Marina (2016)	Netherlands	2016	4	10.5	0.39	0.30	0.30	1.35	2.24	3.7	3.2
Heidari (2016)	Generic	2016	1	1.82	0.58	In mooring	0.06	0.53	0.48	3.5	3
Martinez and Iglesias (2022)†	Europe	2021	1	3.7	0.27	0.11	0.06	0.48	0.81	5.4	4.6

* This publication uses forecast pricing for 2030, rather than present day costs.

† Costs in this publication are a function of distance to shore and water depth. Values of 1000 km to shore and 500 m depth were used for the calculations in this table only.

range of total project costs in 2020. Since these costs refer to the total project cost, they include an average cost of purchasing land, which is highly variable globally, but is estimated to be around 3% of CAPEX in the US, based on the 0.03 USD/W published by NREL (Feldman et al., 2021), although it may be less if the site leases, rather than purchases, the land in question. While installations of solar panels and wind turbines are typically modular, which could in theory constrain the installation capacity of renewable equipment to integer multiples of standard equipment sizes, we consider the size of renewable energy production to units be continuous. Since the whole plant energy consumption (in the order of GW) is much larger than the capacity of a single turbine/panel (in the order of MW), this approximation does not introduce significant error, but prevents the inclusion of a large number of integer variables that significantly increase solution time.

2.1.1. Offshore wind cost estimation

Offshore wind turbines fall into two categories: fixed bottom and floating. Many fixed-bottom turbines have already been installed, and are typically used for near-shore shallow water applications (<50 m). Because they are in common usage, their costs are widely reported; for this analysis, an installed cost of 2,644 USD/MW was used (International Renewable Energy Agency, 2021); this is reflective of the global average installed cost minus the cost of high voltage power transmission to shore (which is about 17% of the total installed cost).

For water depths of greater than 50 m, it is generally considered more economic to install a floating wind turbine (Martinez and Iglesias, 2022). While the literature is in general consensus that floating turbines will cost considerably more than ground mounted turbines (Babarit et al., 2018), only a comparatively small number of authors provide meaningful cost estimates for this technology. The difficulty of estimating costs is further complicated by (i) the rapid reduction in the cost of renewable energy, meaning estimates are quickly outdated, and (ii) the relationship between the wind turbine cost and both the water depth and the distance to shore. Table 1 summarises all data known to the authors from the literature which reports a meaningful breakdown of floating wind turbine CAPEX.

The table demonstrates there is a wide range in reported costs of floating offshore wind, from between 3.5 million USD/MW to almost 6 million USD/MW. However, the transmission line to the shoreline often represents a substantial cost; if this were not required because of co-locating a green ammonia plant, then prices could fall to around 3 million USD/MW. Instead, the user must pay ammonia transport costs, but these are comparatively small because of ammonia's high density; these are discussed in Section 3.3.

In general, the approach of Martinez and Iglesias (2022) was adopted to estimate the cost of wind turbines, since (i) their work is the most recent, (ii) their work most clearly estimates costs as a function of water depth and distance to shore, and (iii) their work provides reasonable estimates compared to those offered by other works.

However, three modifications are made to their estimate. Firstly, and most importantly, the costs of the transmission line and onshore substation are not included in this estimate, since they are not required. Secondly, the turbine costs indicated in their work are considerably higher than those considered by other authors, and may not adequately factor the falling cost of wind energy. For that reason, only the cost of the turbine component is taken from the IRENA average cost of a turbine from 2020. Thirdly, the time allowed for turbine transport in that work does not appear to take into account the low operational windows that may be present for ships in offshore wind farms, which Myhr et al. (2014) argue can increase costs, because hired equipment for installation must wait in port until the weather conditions are safe. For that reason, the time taken for turbine transport was considered to be three times the one-way journey time (i.e. a return journey with an operational window of ~67%), and the costs are adjusted accordingly.

Table 2 shows the turbine cost estimates used in this work for three different turbine sizes. Clearly, the total cost is a strong function of the wind turbine size; predominantly, this is caused by the considerable cost of the moorings, which has a relatively weak dependence on turbine size (although is also the largest source of uncertainty, since these moorings are not widely deployed). While turbines 10 MW in size are beginning to be deployed, we conservatively assume here that the largest turbines available are 7.5 MW, although clearly increasing turbine size is an avenue for future cost reduction.

Table 2
Installed wind costs for different turbine sizes; a depth of 500 m and a distance to shore of 1000 km are used for demonstration purposes. Note costs are in USD unless otherwise specified.

Component	Description	5 MW	7.5 MW	10 MW
Turbine	1.28M USD/installed MW	6.40	9.60	12.80
Platform	8 M€/turbine	8.96	8.96	8.96
Interarray cable	191.6 km for 100 turbines @ 0.3035 M€/km	0.65	0.65	0.65
Turbine Transport	0.0195 M€/day; 2 day install plus journey time @ 20 km/h	0.18	0.18	0.18
Turbine installation	0.24 M€/turbine (includes mooring installation)	0.27	0.27	0.27
Cable installation	0.213 M€/km (Interarrary cable only considered here)	0.46	0.46	0.46
Anchors	0.123 M€/anchor, 4 anchors/turbine	0.55	0.55	0.55
Mooring	Catenary wire (50 €/m wire) + chain (270 €/m) for 50 m	0.31	0.31	0.31
Site selection	0.21 M€/MW	1.18	1.76	2.35
Offshore substation	0.117 M€/MW	0.66	0.98	1.31
Decommissioning	70% of turbine transport, 10% of cable installation, 90% of balance of installation costs	0.41	0.41	0.41
	Total cost per installed MW (USD)	4.00	3.22	2.83

Although Table 2 uses a distance to shore of 1000 km and a water depth of 500 m, the completed plant model uses the actual distance and depth to determine installed costs per MW, although the relationship between these variables and the total cost is small, because of the large contribution made by the turbine and platform.

2.1.2. Offshore solar cost estimation

Offshore solar PV technology is an increasingly attractive option for land-restricted locations. To date, the majority of applications have occurred on inland water-bodies (which are technically simpler than marine applications); in these instances, the panel can reduce evaporation rates from the pond, while operating with increased efficiency because of the cooling effect from the water (Oliveira-Pinto and Stokkermans, 2020). There are a host of other benefits: land preparation costs are not accrued; there is unlikely to be shading from nearby buildings, trees or mountains; and O&M costs may reduce because ocean areas are considerably less dusty (Golroodbari and van Sark, 2021). Although more research is required, preliminary estimates indicate that the local environmental impacts (e.g. biodiversity loss) may be lesser from floating panels than from land-mounted ones (Oliveira-Pinto and Stokkermans, 2020). Additionally, for the application of ammonia which requires steady operation, solar may have a different seasonal profile to wind, and thus there may be synergies from including a second source of power.

Although the majority of floating PV has been installed on inland lakes and reservoirs, pilot projects have been constructed in marine environments in the North Sea (Oceans of Energy, 2021) and the Strait of Johor (Hill, 2021). These projects are more technically complex because (i) the salt water is corrosive and will degrade the panels over time, and (ii) wave action may damage the panels and support structures over time. This wave action may also reduce the efficiency of the panel, although Golroodbari and van Sark (2020) estimate that the effects of panel cooling outweigh those of wave action. For this analysis, it is conservatively assumed that the effects cancel each other out, and that the efficiency of a floating panel is comparable to that of a land-mounted panel.

As was the case for floating wind turbines, it is difficult to estimate the costs of marine PV applications, although the challenge here is further complicated by the lack of consensus among operators as to the best panel superstructure to adopt (for instance, gable structures, solar trees and structures floating on tyres have all been considered). Further, the majority of authors considering floating applications typically perform their analysis on inland reservoirs, and do not consider the additional costs for offshore application, although costs reported are typically between 1000 and 2000 USD/kW (Golroodbari and van Sark, 2020; Rosa-Clot and Tina, 2020). For this analysis, the installed cost of floating solar panels are estimated at twice the cost of a land-based solar panel (i.e. 2×825 USD/kW = 1650 USD/kW). While this nascent technology may well be more expensive in the short term, it is unlikely that it will be widely deployed until it falls below this cost.

2.2. Land restrictions

The approach of the previous section enables the minimum cost of ammonia production to be determined across the globe; however, ammonia production will be constrained by two major factors: land availability, and land competition. Land availability refers to restrictions on land that prevent the installation of renewable energy, because of (i) requirements for other land uses (e.g. urban land/cropland), (ii) land protection legislation in areas of environmental/cultural significance (e.g. National Parks), or (iii) land with a steep gradient.

In order to exclude land that is not suitable for renewable energy applications, the Land Cover Type 1 layer from the MODIS dataset was obtained for each grid square considered in the optimisation (Friedl and Sulla-Menashe, 2019), which classifies land into one of seventeen categories. Different approaches have been considered in the literature for determining whether solar and wind installation is possible on different land categories. For instance, van de Ven et al. (2021) allow 'free' construction in unused areas (e.g. desserts, shrublands, some urban rooftops), and use a competition based model which allows some construction of solar panels in locations with existing uses (e.g. cropland, savanna), but prevents installation in areas that are likely to be environmentally protected such as forests. Deng et al. (2015) also prevents construction of solar PV in forests, but allows wind turbines with ~20% of the land efficiency that they have in other locations. In general, they predict far less land use than other analyses, because of the assumption of an 'availability factor'. This factor varies across countries and land uses, and significantly constrains their estimate of land availability.

Here, we use a hybrid of these approaches, which allows unlimited construction on barren land, and a fraction of construction on other land, depending on its current usage. The fractions adopted are reported in Table S1 in the Supplementary Material. A base, low and high land availability are modelled in order to estimate the possible range of productions. In all cases, construction is not allowed in protected areas, as listed in the UN database (UNEP-WC.M.C. and IUCN, 2021). Construction is also excluded if a site has a slope of greater than 15° (to a granularity of 0.016 degrees). For offshore sites, it is assumed that all ocean area which is not designated as protected is available.

The MODIS dataset, protected land areas, and slope data, is more granular than the weather data that was used for estimation of ammonia LCOA. For each of these measures, land availability was estimated at the finest granularity; the cumulative available area within each of the larger grid squares used for ammonia LCOA estimation was then used to calculate maximum available ammonia production.

Having calculated land availability, the model subsequently incorporates land competition. Here, land competition refers to limitations on ammonia production on land that is suitable for renewable energy production because of other energy production which needs to occur on land. At present, there is little competition for available land, as renewable energy represents a small fraction of total energy consumption; however, in a fully decarbonised economy, this competition is likely to be considerable. We consider production of green ammonia in a net zero emissions context. Prediction of land competition in this context is challenging, as the composition of carbon neutral energy systems remains uncertain; we therefore use two different approaches to estimate land competition, which are designated Method I and Method II.

In Method I, we assume that the land competition faced by ammonia is proportional to its fraction of global energy requirements. If the fraction of land consumed by ammonia exceeds its fraction of global energy demand, then other uses will not be met, which we assume is not acceptable. At present, ammonia production for fertilisers represents 2% of global energy demand (Nayak-Luke et al., 2018), which we take as a base case; a minimum availability of 1.5% and a maximum availability of 3% are considered as sensitivities. Note that this competition factor is not equivalent to the availability factor proposed by Deng et al. (2015); the estimate is therefore conservative in assessing the performance of ocean based ammonia by allowing generous use of land. The competition factor is applied evenly to on- and offshore sites.

In Method II, we assume that land competition manifests as increased costs for onshore sites only, and calculate how large those costs would need to be in order to drive different percentages of production offshore. Costs are expressed in USD/MWh, to provide easy comparison to other renewable energy production projects. Eq. (1) links the increased costs of electricity to an increase in the LCOA.

$$\begin{aligned}\text{Increase in LCOA} = {} & \text{Increased costs in USD/MWh} \\ & \times \text{Annual Operating Hours} \times \frac{MMTPA}{10^{-6} tons NH_3} \times \\ & \times \Bigg[\sum_{\text{Renewables}} \text{Renewable load factor} \\ & \times \text{Renewable installation in MW required} \\ & \quad \text{for 1 MMTPA of capacity} \Bigg] \end{aligned} \tag{1}$$

Results are shown in the supplementary material (Figure S3). The equation is essentially a unit conversion — the product of the annual operating hours, load factor and renewable installation gives the MWh per MMTPA of ammonia produced; when this is multiplied by the increased costs per MWh of electricity, it is translated into the increased costs per ton of ammonia produced each year.

2.2.1. Renewable energy land requirements

Estimates for wind turbine land use requirements vary from 100 to 200 km^2/GW of installed capacity. In order to minimise wake effects, we assume a space efficiency of 200 km^2/GW (Salmon et al., 2021).

Estimates for solar land use requirements also vary from different authors — we adopt the method from van de Ven et al. (2021), which varies the packing of solar panels on the basis of latitude to maximise efficiency (since at higher latitudes panels must be further apart to prevent shading). The method is modified to report the land usage in km^2/GW by using the space efficiency of a standard solar panel (First Solar, 2018).

To convert renewable energy land requirements into ammonia production capacity, we assume that complete overlap is allowed between wind and solar farms. In reality, access roads required by wind turbines, and the shading effect of these turbines, will prevent this idealised overlap; however, it provides the largest possible estimate of land production capacity and is therefore conservative for the assessment of ocean performance. For similar reasons, the area of the hydrogen and ammonia production itself is considered to be negligible in comparison to the area of the renewable energy farm.

3. Results

This section of results is divided into three subsections. In the first section, we estimate only the costs of production without land limitations, considering both a (hypothetical) case in which the onshore and offshore costs of wind are equal (purely to assess the quality of the wind resource in the ocean), and a more realistic case in which the true costs of offshore renewables are factored into the analysis. In the subsequent sections, we expand our analysis to represent the value of offshore production more meaningfully. The second section investigates the impact of land limitations on ammonia production at each of the sites, and shows the relationship between cumulative global production and LCOA. The third and final section includes the costs of additional infrastructure requirements associated with offshore production (floating platforms) and onshore production (pipelines to shore).

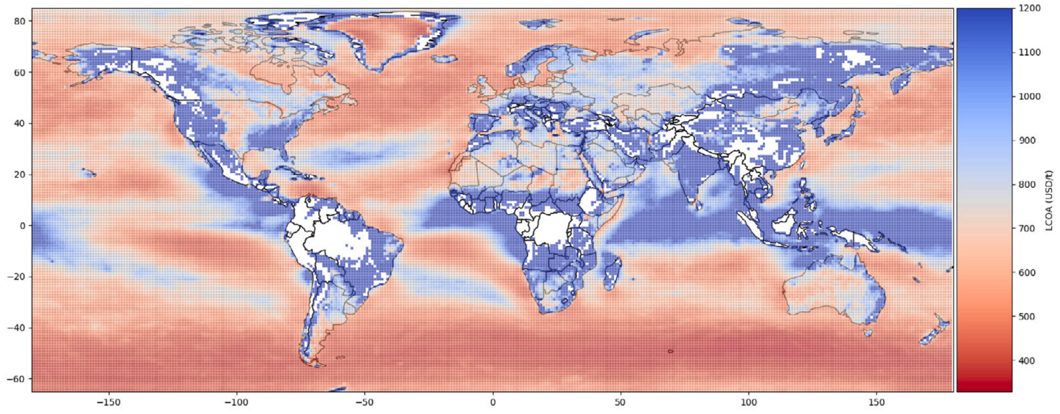
3.1. Production costs

Two cases were considered for the production costs: a hypothetical case in which costs were equal on and offshore, whose purpose is to show the quality of the ocean resource; and a more realistic case in which solar installation is allowed on land, and the additional costs of offshore renewable installation are included in the estimate. The results of the two cases are shown in Fig. 2

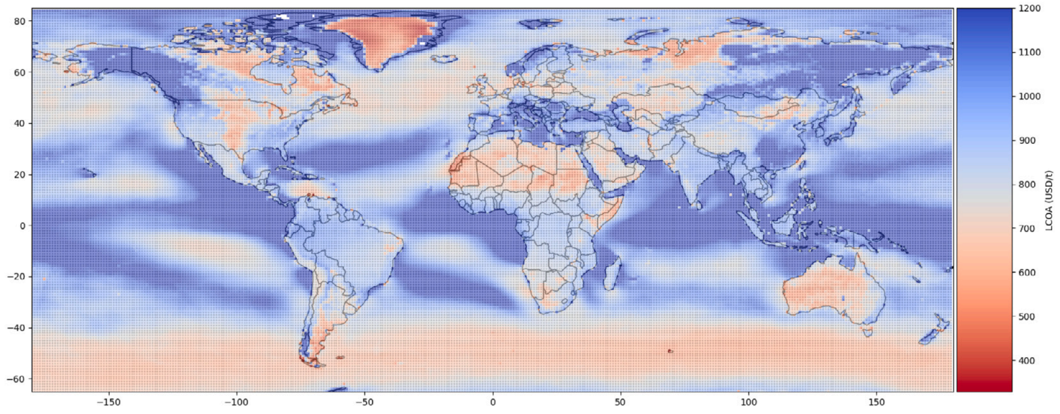
There are two points which are noteworthy for the hypothetical wind only cases. Firstly, the model cannot converge at many land-based sites; this occurs because there is a maximum cap on the wind turbine installation of 20 GW in order for the model to converge more quickly — although it sometimes causes the model to fail to return results, this will only occur in locations where the ammonia cost would have been extremely high, meaning they are unlikely to be used to produce ammonia in the future. Secondly, in this raw comparison of wind resources which neglects the realistic costs of a floating plant, the ocean sites far outperform land based sites. In particular, the wind band at very southerly latitudes (from about −65° to −45°) has extremely cheap ammonia. This demonstrates that the wind resource quality in the oceans is superior for ammonia production to that available on land.

However, this performance is not replicated when the true costs of offshore wind installations are also considered, as is evident in Panel (b) of Fig. 2. Fig. 3 shows the comparison more clearly, by showing the cumulative production at a given price point for the two cases shown in the heat maps. One additional hypothetical case is included, in which cheap solar and electrolysers are available on- and offshore. This latter case represents a likely future in which the costs of solar PV and water electrolysers fall more rapidly than the cost of wind turbines. Cheap water electrolysers will typically benefit solar dominated sites more than wind dominated sites because good solar sites provide cheaper electricity, but at a lower load factor than good wind sites; the cost of oversizing the electrolyser to accommodate this low load factor is smaller as the electrolyser becomes cheaper. Since, in general, the solar resource is superior onshore, this reduced cost of solar panels will typically benefit onshore locations more than offshore locations. For this section, it was assumed that the entire area demarcated by a location could be covered in wind turbines with a land requirement of 200 km^2/GW, or by solar panels with a land requirement determined by their latitude. (Salmon et al., 2021)

Fig. 3(a) demonstrates that the superior ocean resource means that it produces considerably more very cheap ammonia than land based-sites, all costs being equal. However, factoring in the increased costs of floating wind farms significantly increases the LCOA of the associated ammonia; it cannot compete with land-based ammonia in this regime — for it to be competitive, the global ammonia demand would need to be in the order of 10^4 MMTPA, which is considerably larger than demand today, which is marked on the figure as approximately 200 MMTPA.



(a) - Wind only, onshore and offshore costs equal



(b) - Wind and solar, true onshore and offshore costs

Fig. 2. Heat maps for two different sets of results. (a) — Top: Wind only, with equal costs on and offshore, purely for demonstration of offshore wind potential; (b) — Bottom: True costs for on and offshore wind and solar. In order to maintain a readable colour gradient, locations with an LCOA > 1200 USD/t were shown using the same colour as those with LCOA = 1200 USD/t.

The cost increase across all sites is fairly uniform, in the order of 40%. A 40% cost increase is consistent with expectations; although the turbines themselves have increased in cost by more than a factor of 2, there are many other components in the ammonia production process (i.e. electrolysers, Haber–Bosch) with significant costs that are largely unchanged in this mode (although the infrastructure required for them to float may be expensive — see Section 3.3).

The final case shown on the figure gives an indication of how this cost balance may shift as the price of solar panels continues on its precipitous decline. In this case, the cheapest ocean and land sites become even cheaper than in the previous wind and solar case, but this difference is attributable to the reduction in the cost of electrolysis units, since the cheapest sites are still the ones with an excellent wind resource. Consequently, the cheapest land and ocean sites do not substantially change in cost relative to each other. Panel (b) indicates that most of the influence of the reduction in price of solar panels is felt at sites with an LCOA greater than 400 USD/t (in the hypothetical cases); this is where the most deviation is observed between the lines for the land cases comparing real and hypothetically low solar prices. The relationship between LCOA and wind usage is approximately the same at both land and ocean sites.

At the cheapest sites in the ocean, floating solar is not installed, even though it is allowed, because the wind resource is so superior to the solar resource (many of the best locations are at absolute latitudes greater than 40^{deg}). Land sites make greater use of solar, but it is still only enables a fairly small reduction in cost at the best sites — in the order of 5 USD/t. This makes the cheapest land sites marginally more competitive against the cheapest ocean sites. It is unlikely that continuing falls in the cost of solar panels will therefore significantly affect the distribution of ammonia production predicted here; it should also be noted that floating wind turbines may fall in price as quickly as solar panels, since they have yet to be used to a significant extent (Wiser et al., 2021).

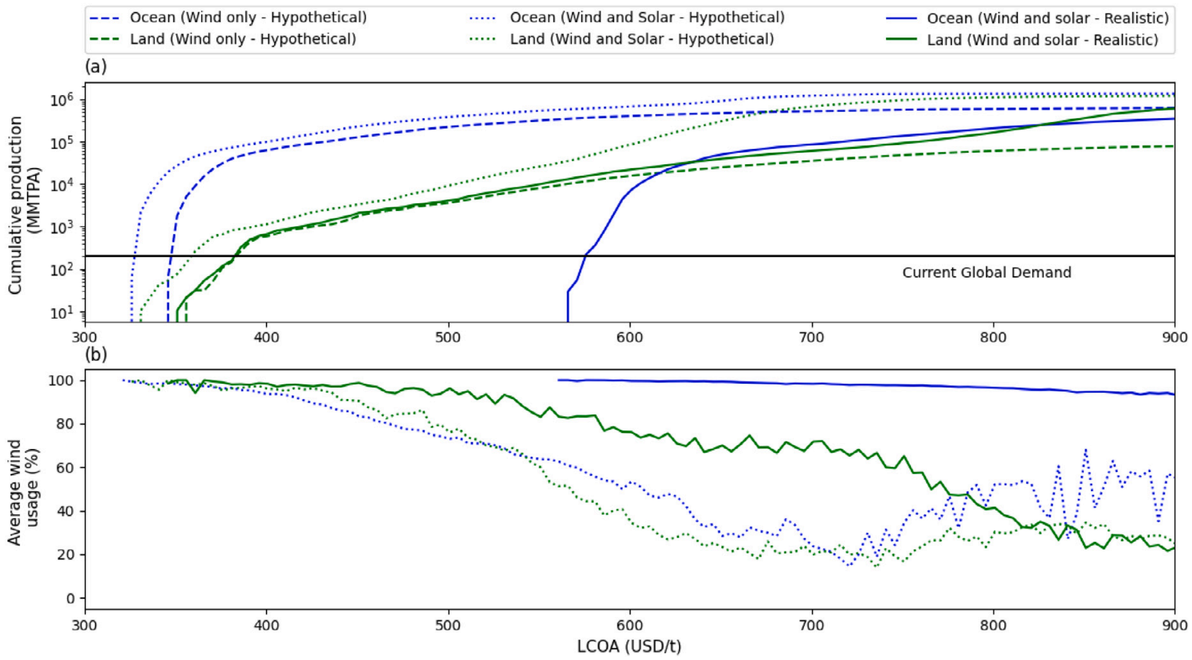


Fig. 3. Comparison of cases by cumulative production. Two sets of hypothetical cases are included in which on and offshore costs are equal — in the first, only wind is allowed, and in the second, both wind and cheap solar/electrolysers are also allowed. The solid lines represent the realistic cases, using the true costs of on- and offshore installation.

There are some interesting results at comparatively poorly performing sites (i.e. LCOA > 600 USD/t for the hypothetical cases); in these locations, because the capacity of solar panels to generate far more electricity per area of land, the total production capacity increases markedly; in fact, it becomes almost as high on land as in the ocean, even though the total area of the ocean is almost triple that of land. This indicates that, while the solar resource on land in general outperforms the solar resource in the ocean, this outperformance is not sufficient to produce cheaper ammonia than using the excellent wind resource available in the ocean, or on some land locations.

3.1.1. Impact of ocean depth

Fig. 4 shows the relationship between the cost of ammonia and how far a site is from the shore for the realistic case.

As outlined in Section 2.1.1, the total cost of the wind turbine is a function of water depth and distance to shore; however, the plot demonstrates that these variables have little dependence on either the minimum or the average LCOAs observed at a nominated ocean depth or distance to shore. This is because the fraction of floating wind turbine costs associated with mooring and installation (which vary as a function of depth) is small compared to the turbine and floating substructure (which do not depend on depth). The small increase in cost of the turbine does not translate to a meaningful increase in the cost of ammonia, as the quality of the wind resource is of greater significance. For locations comparatively close to shore (<500 km), there is an inverse relationship between distance and LCOA, indicating that in general, better resources are available further from the shore; this is likely also the reason that the LCOA at depths <50 m (where cheaper fixed bottom turbines can be used) is not significantly less than the LCOAs at greater depths.

3.2. Land availability

The previous subsection compared the quality of the resources, and demonstrated that the costs of floating renewable energy generation are too large to enable ammonia to be produced on the ocean that is cheaper than that produced on land, despite the superior wind resource in the ocean. Even a potential increase in demand by a factor of 5 to 10^3 MMTPA (which would provide enough extra ammonia to supply the maritime industry and considerable energy/hydrogen trade via ammonia) would not justify the use of ocean sites, since the ammonia cost at that production rate still exceeds the cost on land by ~160 USD/t.

However, the results in Fig. 3(a) assume all land can be used ammonia production, which is not realistic — for instance, it appears on that figure that Greenland would be a suitable location for production, but given environmental concerns and the difficulties of production in very cold climates, it is not likely that it would be suitable for large scale chemical production. Limitations on ammonia production due to land availability can be classified into two categories: given (i) land use restrictions imposed by other sectors – predominantly agriculture, but also forest protection, urban and built up land (Food and Agriculture Organisation of the U.N., 2021) – and (ii) land competition from other energy generation, which will increasingly demand more land as economies decarbonise. In this section we will explore the impact of these land limitations on production capacity at the best locations.

Three cases were considered for land use restrictions – a base case, as well as a low and a high land use case – and the results are shown in Fig. 5 (note this figure assumes construction of both wind and solar, identical to the realistic case shown on Fig. 3). In assessing global demand, we focus on global demand for fertilisers; although we predict that ammonia will be consumed in other sectors, global fertiliser demand is more likely to be stable and therefore is more reasonable for forecasting; however, the logic could be extended to other applications.

We use two approaches to model land competition from other renewables: a land limitation approach in which the fraction of available land which can be used to make ammonia is equal to the fraction of global energy required to produce that ammonia (Method I), and a cost competition approach, in which ammonia can be produced on all available land, but an additional charge must be paid to overcome competition from other renewable energy generation (Method II — for more detail, see Section 2.2.1).

Using Method I for land competition estimation, the economic case for ocean-based ammonia production becomes considerably more attractive, and begins to become competitive with land based production

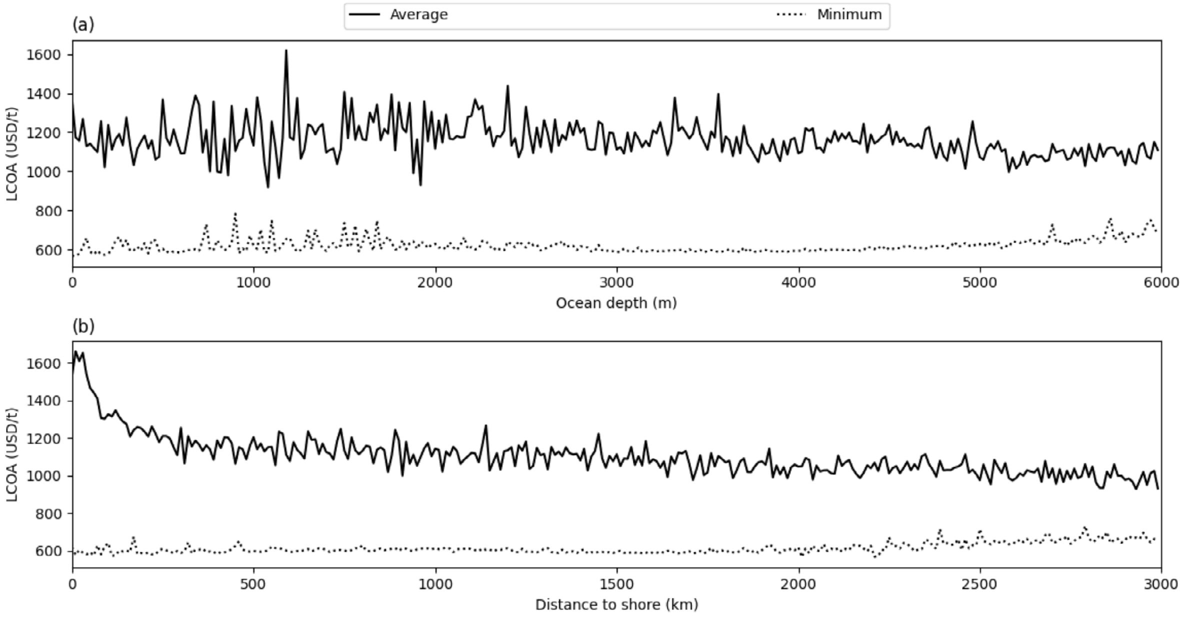


Fig. 4. Impact of ocean depth and distance to shore on average and minimum ammonia cost. (a) — Top: Impact of depth. (b) — Bottom: Impact of distance.

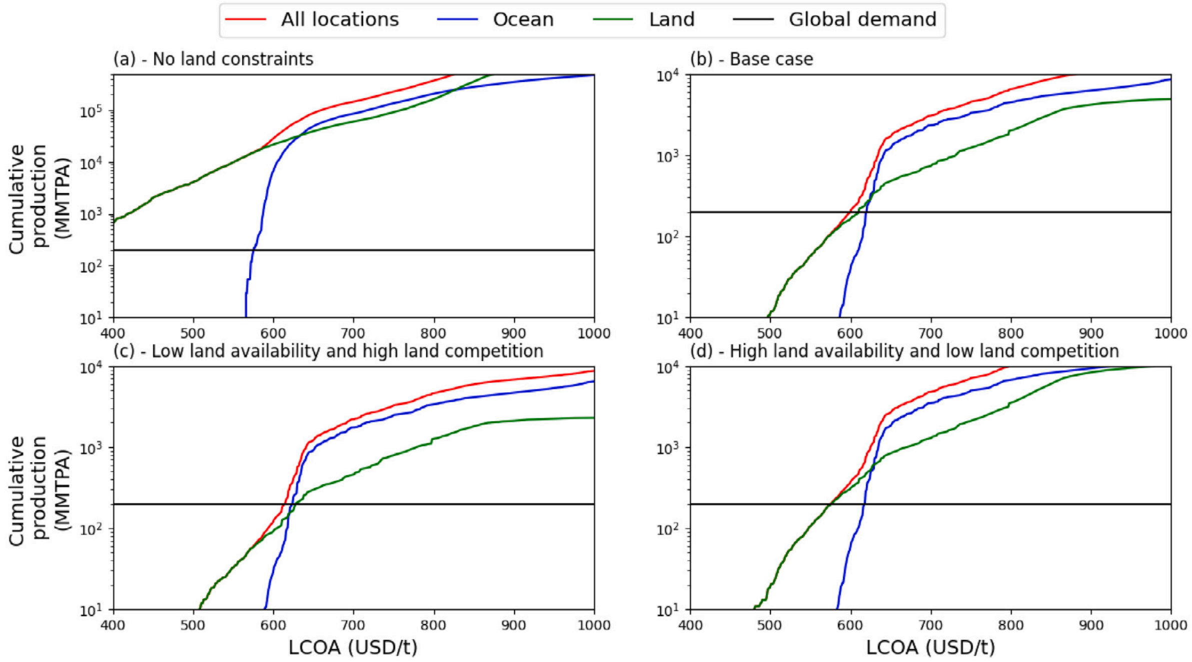


Fig. 5. Impact of land availability and competition on ammonia production costs. (a) — Top left: No land constraints; (b) — Top right: Base case; (c) — Bottom left: Low land use (i.e. low availability and high competition); (d) — Bottom right: High land use (i.e. high availability and low competition). Note the scaling on the *y*-axis of panel (a) differs from the other three plots. These plots use Method I for estimating land competition; for plots using Method II, see the Supplementary Material Figure S3.

around the current global ammonia production rate. In the base case, Fig. 5(b), around 15% of ammonia is made most profitably in the ocean (measured by the vertical distance between the red and green lines where the red line crosses the global demand); in the low land availability case, Fig. 5(c), this rises to as high as 33%. Even in the high land availability case, Fig. 5(d), a small amount of ammonia (around 1 MMTPA) would also be profitably produced offshore.

The results in Fig. 5 are calculated for the whole globe; in specific regions, the incentive for ammonia production on the ocean may be greater. For instance, the UK has both high population density and a sizable agricultural industry, meaning it has little available land but large fertiliser demand. The UK specific results are shown in the Supplementary Material (Figure S1), and demonstrate that even in the base case, as much as 50% of its ammonia may be produced offshore. Because of very restrictive land restrictions for onshore wind farms in the UK (Windemer, 2019), and a comparatively unreliable solar resource, the low availability case is more likely, in which case almost 100% of ammonia will be produced offshore. While importation is also an option for the UK and other similar regions, near offshore production may be preferable to maintain energy security, and to avoid long distance shipping costs for fuel.

Using Method II for land competition estimation, we estimate that if land costs accrue which increase the levelised cost of electricity production by 10 USD/MWh, then about 15% of production will move offshore (the same as in the base case for the first approach). This is approximately equal to the costs of moving a wind farm from a site with a load factor of 40% to one with a load factor of 30%, or to the cost of moving a solar farm from a site with a load factor of 25% to one with a load factor of 18%. In other words, it is similar in magnitude to relocating renewable energy production from an excellent site to an above average site, and is therefore a plausible estimate for the cost of land competition.

3.3. Infrastructure requirements

An important consideration which has yet to be factored into the above analysis relates to the broader infrastructure requirements to enable ammonia to be produced on a floating plant: these include the platform on which the ammonia is produced and the cost of transport to shore (the costs of floating the wind turbines themselves have already been factored into the cost of equipment). Production on platforms should be technically achievable using similar technologies to those already employed by the offshore oil and gas industry, although the costs may be considerable. Having been produced, the ammonia could be delivered to the nearest point on the shore, but it would be more practical to deliver ammonia to a nearby demand centre. In that more realistic case, transport costs also accrue for ammonia produced onshore, in pipelines to ports, and shipping to demand centres. The purpose of this section is to understand how offshore production impacts the costs of delivery, on top of the cost of production. In order to do so, we consider delivery to two demand centres: Hamburg in Germany and Yokohama in Japan. Both countries have announced intention to import ammonia as fuel in the future, and these ports are also useful proxies for significant future demand for ammonia in Europe and East Asia respectively.

Costs for constructing offshore equipment may be significant, but are usually confidential. In a small number of cases they may be avoided if (a) there is shallow water or an island nearby on which to base an ammonia plant, or (b) there is an oil and gas rig which can be repurposed for hydrogen production. However, in the majority of cases, a new floating structure will be required. There are a range of possibilities available for a floating plant: it could be either a platform (as used in the oil and gas industry), or a production ship. Wang et al. estimate a cost of 100 million USD per platform (Wang et al., 2021), which is considerably less than the ~500 million USD estimated by Kaiser and Snyder (2013) (for a semi-submersible platform, averaged between 2008 and 2013), although this figure is for an entire drilling rig, inclusive of equipment, and therefore represents an upper bound on the true cost. We therefore conservatively take the cost of an offshore platform to be in the order of 200 million USD.

The impact of this additional cost on the LCOA naturally depends on production capacity; based on the weights of electrolysers specified by NREL (Ruth et al., 2017), and the weight tolerances specified in Kaiser and Snyder (2013), the approximate capacity of these platforms would be 1 MMTPA, meaning the increase to LCOA from platform operation would be approximately 15 USD/t. For comparison, a 600 km ammonia pipeline (the average distance from the coastline for land locations with an LCOA < 600 USD/t and which are therefore competitive according to Fig. 5) at that capacity would have a cost of around 12 USD/t (Salmon et al., 2021); that cost may be doubled if desalinated water must be pumped from the coast line, although we do not consider that cost here. The land and ocean based infrastructure requirements are therefore of a similar order of magnitude, although a significant uncertainty remains.

Shipping cost advantages should also be considered. These will differ for different countries; however, in some cases, ocean locations may hold considerable opportunity to reduce shipping costs. For instance, the majority of very cheap land locations are in the Western hemisphere (i.e. Northern Africa and South America); these will have very large shipping distances to Japan, which is forecast to be a major demand centre. The shipping distances from the very good marine locations in the Southern Ocean are about half that distance, which would amount to savings of ~20 USD/t (based on estimates in Salmon et al., 2021); on the other hand, those savings would be reversed for Germany (which has also stated its intention to import hydrogen in the form of ammonia), which would be better off importing from Morocco than the Southern Ocean.

To factor in these infrastructure costs, a delivered cost of ammonia to both Hamburg and Yokohama was estimated for each potential production location. Land transport costs were factored using a cost of 2.56 USD/t/100 km of pipeline, as per previous work from these authors (Salmon et al., 2021), and land transport distances were calculated to the nearest port (with an overdesign factor of 10%). Maritime distances between ports were estimated using shipping routes available in the AIS database. Maritime distances from offshore production sites to Hamburg and Yokohama (which are not major shipping routes) were estimated using the PortWorld online calculator. Shipping costs were then estimated, using parameters reported in the supplementary material. It is assumed that the ships are powered using the onboard ammonia. The results are reported in Fig. 6.

The infrastructure costs reduce the economic case for offshore production, although it is still viable for shipping to east Asia in the base case, representing around 7% of production (and more than 25% of production in the low land availability case). However, for shipping to Europe, because of the proximity of cheap land production sites in West Africa, it is always preferable to used land based production. For the East Asia case, all ammonia is produced in deep water far from the shore; the average distance for the cheapest 200 MTPA of ammonia is 180 km from shore (compared to a global average of 30 km for offshore wind today), and the average water depth is approximately 400 m (well more than the typical depth of < 50 m for most offshore wind farms today).

Therefore, while it is not possible to predict the precise fraction of ammonia that will be produced on the ocean without a detailed predictive model of ammonia demand, it does not appear that the inclusion of infrastructure costs will prevent it from being a viable production method in the context of land limitations.

4. Conclusions

The ocean is a vast area of untapped potential, possessing a high speed, low variability wind resource; green ammonia provides an opportunity to unlock that potential by allowing energy to be stored and transported more cheaply and flexibly than transmission via cable. However, the costs of offshore wind turbines are more than 200% larger than those used onshore, meaning the best sites in the ocean are not able to compete with the best sites on land. Despite those considerable costs, though, competition for land from other sectors and other renewable energy uses may create an economic climate in which it will be optimal to produce ammonia in the ocean, even in deep water far from the shore. This is largely because the total area of the oceans is much larger than the total land area, and there is likely to be less competition from other uses. While there will be additional infrastructure costs for floating production, these are somewhat offset against the cost of pipelines, and reduced shipping distances, meaning offshore ammonia can still be competitive for some demand destinations. Therefore, even given the very high price of offshore wind turbines, offshore plants may be key to meet future global ammonia demand affordably.

The opportunities from offshore ammonia production are considerable: mid-journey, ocean refuelling of large ships; increased capacity for countries to become energy independent if they have limited land availability but quality marine wind resources (e.g. the UK); and renewable energy production with considerably less risk to local land environments. This research has shown that there is a serious possibility that the use of this technology will be economically justified in a decarbonised world.

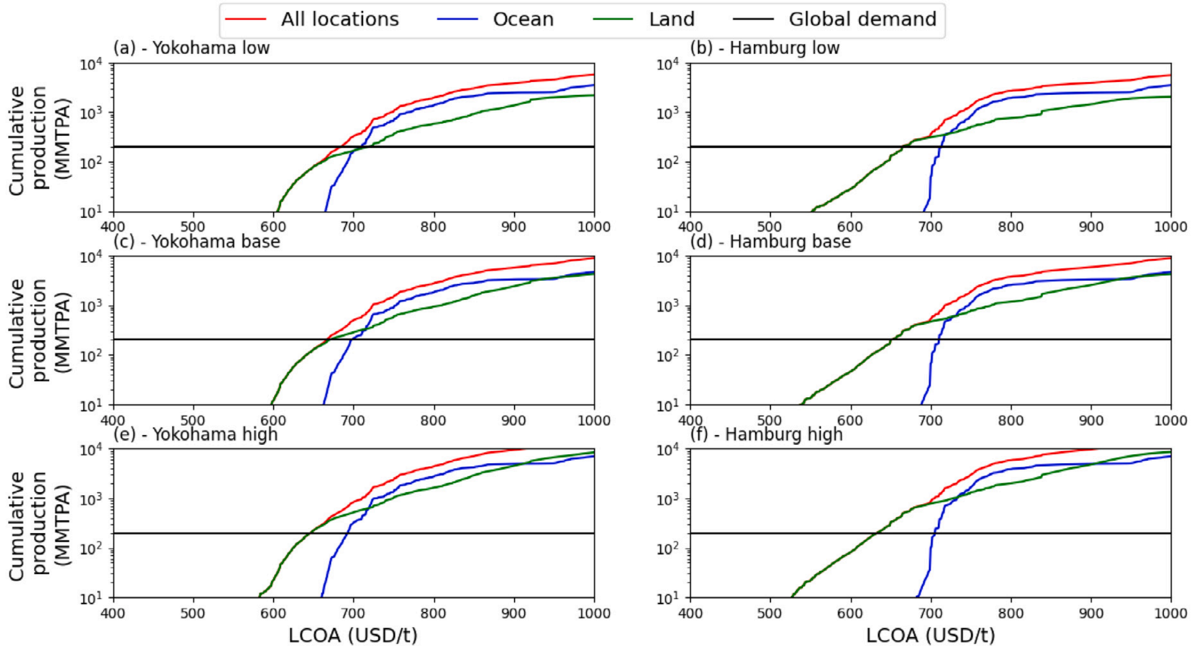


Fig. 6. Impact of infrastructure constraints and land availability on delivered costs of ammonia. Left plots show delivered costs to Yokohama; right plots show delivered costs to Hamburg. All three sensitivities on land availability are also shown.

List of acronyms

ASU	Air separation unit
CAPEX	Capital Expenditures
HB	Haber–Bosch
LCOA	Levelised cost of ammonia
LPG	Liquid propane gas
MILP	Mixed integer linear program
MMTPA	Million metric tonnes per annum
NPV	Net Present Value
OPEX	Operating Expenditures
USD	US Dollars

CRediT authorship contribution statement

Nicholas Salmon: Conceptualisation, Data curation, Methodology, Software, Validation, Formal analysis, Writing – original draft. **René Bañares-Alcántara:** Conceptualisation, Project administration, Resources, Supervision, Validation, Writing – review & editing.

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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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.133045.

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