WEIGHING THE EU'S OPTIONS: IMPORTING VS DOMESTIC PRODUCTION OF HYDROGEN/E-FUELS

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EXECUTIVE SUMMARY

The Russia invasion of Ukraine has brought into focus some of the risks of a global energy market, with gas supply constraints and the resulting price volatility placing great strain on Europe's industries and citizens. A reduction in Europe's reliance on natural gas will be a natural consequence of decarbonisation. However, by seeking to import a significant proportion of its future energy in the form of hydrogen and derivatives, there is a potential supply risk of continued reliance on foreign energy supply. Many of the countries likely to export hydrogen to Europe are in the Global South, leading to concerns about resource exploitation, environmental impacts and delaying local decarbonisation. This report finds that this is a complex situation without simple right or wrong answers. There are benefits and risks associated with the EU importing hydrogen, both to the exporting countries and to the EU itself. This report for Transport & Environment seeks to understand the situation, by performing case studies on six countries likely to export hydrogen to the EU. The study includes the state of the electricity system in each country, environmental, social and economic factors, a review of announced projects and a counterfactual consideration of the situation should each country not export hydrogen. The study also considers the benefits and risks and the EU focussing on domestic hydrogen production rather than import.

Demand targets

In European policies, numerous hydrogen demand scenarios are presented. Different hydrogen targets for different hydrogen-based energy vectors are found in policies including Renewable Energy Directive (RED), RePowerEU, ReFuelEU and Fuel EU regulations. From these policies only RED and SAF are legally binding, and rest of the documents are non-binding in nature.

Environmental Impact

The environmental impacts associated with green hydrogen production plants mainly pertain to the large-scale renewables required to power them. Countries with large areas of desert, such as five of the six countries chosen for this study have, are ideal locations for solar and wind farms given their consistent sunlight and wind patterns. A concern for large scale implementation of these renewables is the introduction of shading that could potentially change the existing ecosystem, in turn affecting local biodiversity.

Co-locating renewable energy plants can prove cost effective and maximise land use and the possibility of grid connection. The actual construction of these plants can have negative impacts to the surrounding environment, including soil compaction, alteration in drainage and disrupt local flora and fauna. In addition, those plants constructed in rural areas will require the creation of new roads in order to construct, operate, and distribute the hydrogen.

Review of case-study countries

Some of the countries studied have 100% electricity access and grids with high emissions intensities, highlighting a competition between green hydrogen production and grid decarbonisation. However, the grids are large meaning the reprioritisation of potential renewables for hydrogen would not significantly change the grid. These countries include Egypt and Morocco where the reprioritisation of renewables could reduce electricity emissions by 7.2% and 42% respectively.

Other countries have 100% electricity access, and grids with high emissions intensities, highlighting a competition between green hydrogen production and decarbonisation. Namibia is the only exception to this with 47% electricity access. But these grids are small or medium in size meaning the reprioritisation of potential renewables for hydrogen would significantly change the grid, sometimes requiring a transformation of up to 10 times in generation. These countries include Chile and Namibia whose grids could be completely decarbonised by a reprioritisation, and green hydrogen developed, as well as Oman where a decrease of 88% in the electricity emissions could be seen.

Norway is an outlier as the country has 100% electricity access and a grid with a low emissions intensity. If renewables originally meant for green hydrogen were reprioritised for grid decarbonisation, the grid could be fully decarbonised and green hydrogen developed. It must be noted that in all 6 cases there would be consequential emissions elsewhere, if renewables are reprioritised, to make up the shortfall. These consequential emissions could be greater or smaller than the in-country avoided emissions, depending on the hydrogen production method.

The 6 countries studied have varying levels of inequality, unemployment, and poverty (with Namibia having the worst socio-economic outcomes and Norway the best). If well managed, the development of the hydrogen economy could catalyse local development and job creation in the various jurisdictions and ideally alleviate some socio-economic pressure.

A potential 2.6Mt/yr of hydrogen could be exported to the EU from the 6 countries discussed, which is significantly below the 10Mt/yr ambition stated in RePower EU. Countries such as the USA, South Africa and Saudia Arabia are likely to export to the EU, reducing this shortfall. Other projects are likely to reach FID soon, increasing the potential supply to the EU. However, some projects will fail to reach the production stage.

Supply chain risk

The transition to using hydrogen is expected to reduce reliance on energy imports. There are concerns about exposing the EU to supply risk due to reliance on import for hydrogen. In order to assess the risk, we considered Chile as the single largest exporter and how cutting off the supply from it will impact the supply chain. Accounting factors like the substantial expected domestic production and hydrogen storage indicate the supply risk for hydrogen is extremely minimal.

Domestic production

Producing hydrogen within the EU for domestic consumption has many advantages, which include:

- Enabling benefits of high renewable potential in the North Sea and Iberian Peninsula to extend beyond these regions; Lower transport and distribution costs of hydrogen; Job creation, improved balance of trade and technology leadership; Reduced risks associated with import of energy; Lower overall energy requirement and fewer losses compared to sea routes and hydrogen carriers.

Potential downsides from EU domestic production include:

- Diverting valuable foreign investment from lower income countries to the EU; Delaying EU grid decarbonisation due to limited availability of renewables; Conflict with land-use and population; Higher lifecycle emissions due to lower (solar) capacity factor; Higher land and labour costs.

This study finds that mass import of hydrogen from beyond the EU may not be cost competitive with hydrogen produced within regions of the EU with strong renewable potential. Morocco possesses some of the best overlapping wind and solar resources in the world and is positioned well geographically to support hydrogen demand in Europe. Even with these advantages, the lack of transport infrastructure and the cost entailed in its development presents a major challenge. Further investment is required in this area if hydrogen is to effectively support the energy transition, and further study is necessary to assess the feasibility of different solutions and identify those which are both cost-effective and equitable.

The dynamics of supply and demand, and the uncertainty therein, are also likely to shape the future of the import and export markets. While many entities are interested in the supply of hydrogen, the demand currently does not exist and investment, leadership and support are missing at government and state levels.

Recommendations for further work

Given the challenges within the EU related to the rate of renewables roll-out and hydrogen projects progressing, it is recommended that a stocktake be performed on the findings within the 2020 report "Renewable electricity requirements to decarbonise transport in Europe with electric vehicles, hydrogen and electrofuels" by Ricardo for T&E. This will help to understand whether the EU is still on-track to meet its hydrogen demands or will have to rely on imports and the challenges this would entail.

This report shows that while there are many potential benefits for countries planning on exporting hydrogen to the EU, especially those in the Global South, these benefits are by no means guaranteed. If the economic interests of international developers are allowed to dominate, there may instead be environmental and socio-economic downsides. It is recommended that Transport & Environment work with relevant stakeholders and experts to draw up a list of guidelines or requirements for governmental or institutional funders to ensure projects focussed on export to the EU consider equitable outcomes and avoid exploitation. Publication of such guidelines may also encourage offtakers to consider the broader sustainability of hydrogen they procure.

1. INTRODUCTION

The Russia invasion of Ukraine has brought into focus some of the risks of a global energy market, with gas supply constraints and the resulting price volatility placing great strain on Europe's industry. One way in which Europe might effectively reduce the exposure inherent on this dependence is in following through with its decarbonisation plans and moving away from imported fossil fuels. According to the RePowerEU Plan, the EU aims to import 10million tonnes (Mt) of renewable hydrogen by 2030 from countries with greater renewable resource availability and the necessary land for such projects. In pursuing H_2 production and export to the EU, it is important that the EU, funders, and the exporting nations properly manage the process to mitigate against detrimental, unintended consequences. The resource curse is a well-known concept whereby a country with an abundance of natural resources underperforms economically despite this resource advantage. This has historically played out in various developing contexts in sectors such as oil and gas and mining. The tenets of a just transition could be adopted to ensure a cycle of benefit extraction and cost localisation (socio-economic and environmental) is not perpetuated. The production of green H_2 should ideally catalyse further socio-economic benefits for communities including capacity sharing and local skills development, creation of new industries and decarbonisation of existing ones resulting in job creation and community involvement through ownership and management of assets. Further, the environmental gains of export focused projects should benefit all stakeholders, domestic and international.

Multiple studies show Europe is likely to procure much of its pure hydrogen from North Africa, a region which has a history of political instability and areas of which hold values that run counter to those considered fundamental in Europe. Simultaneously, the US has developed the Inflation Reduction Act (IRA). The effects of this act disadvantage European industry, particularly vehicle exports. In answer, the European Commission is developing a policy response which could include provisions to boost its own domestic industry. This could include support for development of a domestic energy industry.

As far back as 2020, the General Secretariat of the Council was calling upon the EC to make use of the potential for domestic hydrogen production to reduce import dependencies[1]. The hope was this could stimulate a domestic energy industry providing green jobs across the entire value chain including the renewable electricity industry.

The purpose of this study is to assess six countries that are well positioned, or have announced ambitions, to export considerable volumes of low carbon hydrogen to the EU, considering benefits and risks for both parties.

The initial part of this study included the data collection and review of announced green and blue hydrogen projects within each of the six chosen countries. In order to gain a more realistic view to the expected production and potential export volumes, only projects at feasibility, construction, final investment decision (FID), and operational stages were counted. In addition, projects of small size[2] and/or use case, such as direct injection of hydrogen to the grid, were not counted as part of this exercise.

This data was then used to identify total potential production and export potential, as well as a counterfactual scenario for each country to better understand an outlook whereby the renewables earmarked for hydrogen production were instead used for grid decarbonisation. Each country section includes a real-world project case study and assessment of the cumulative land and water requirements for the total announced projects.

In addition, this study includes an assessment of the supply chain risk, the benefits of domestic production, including alignment with current targets, a best case and realistic scenario, as well as the potential cost of production.

The focus of this study is solely based on the medium term, including all production volumes, estimates, and analysis. It is worth noting, however, that estimates made for the real-world case study for each country include the fully completed projects, which in many cases is set further than 2030.

1.1 SELECTION OF THE STUDIED COUNTRIES

Chile, Egypt, Morocco, Namibia, Norway, Oman, Saudi Arabia and South Africa were selected for initial analysis using preliminary criteria. To narrow down the choices, the countries with most advanced plan for

[1] Towards a hydrogen market for Europe: Council adopts conclusions - Consilium (europa.eu)

[2] Projects with less than 4000t/y hydrogen (or size 25 MWe) production were not included.

export to the EU and diverse sources in their energy mix were chosen. These criteria included the ease of export (considering sea routes from port of Rotterdam), major sources of energy[3], percentage of economy based on fossil fuels, percentage of population having access to electricity[4], carbon sources and water stress in the region[5]. Additionally, official discussions between these countries and European countries regarding the export of hydrogen were also considered while making the selection. The summary of the assessment is as below:

- Chile has over 47% of contribution renewable energy sources in the electricity generation mix making it a desirable choice for green hydrogen export to the EU. Chile has the longest shipping distance from EU ports among all the countries and is a highly water stressed region ranking fourth in order of increasing water stress. In the Chilean hydrogen strategy, almost one-third of the produce is planned for export to the EU. Of the two electro-fuel (e-fuel) projects: one is at feasibility stage and the other under construction. Both projects plan to use direct air capture for carbon dioxide.
- Egypt has 12% renewable energy consumption in its electricity generation mix. It has several hydrogen, ammonia, and e-fuel projects in concept and feasibility stage. It has a short shipping distance to Europe. Egypt has the second highest water stress next to Oman. In its hydrogen strategy, Egypt has not stated the details of hydrogen export.
- Norway has almost 100% renewable energy sources in form of hydro and wind energy in its electricity mix, which presents a good opportunity for generating green hydrogen. In addition, it offers the pipeline opportunity and is the least water stressed country of the selected countries. It has an upcoming e-fuel project that will make use of biogenic carbon and direct air carbon capture. Norway does not have any specific export targets in policies although some projects particularly aim to export to Europe.
- Namibia has a clean grid compared to nations besides Norway, with over 95% renewable energy in its generation mix making it an optimal choice for production of green hydrogen. However, only 47% of its population have access to electricity. It has extremely high water stress, but lower than Chile, Oman and Egypt. The distance from Europe is similar to Oman. The majority of planned projects in the country aim to export to the EU.
- Morocco has over 18% renewable energy in its generation mix, which is greater than other Middle East and Northern Africa countries in consideration. The country intends to export hydrogen as well as consume it domestically through its upcoming projects. It offers choice of pipeline export and also has direct access to European market through a short sea route. It is the country with the second least water stress. In 2022, the EU and Morocco signed the green partnership[6], and the country has ambitious plans of exporting hydrogen to the EU.
- Oman currently has zero contribution from renewable energy in its electricity mix and it has highest water stress among all the nations considered. It was chosen due to extreme water constraints to understand how water stressed regions would source the water required for the electrolysis process. It has two under-construction hydrogen-ammonia plants. It is highly reliant on natural gas and oil. Recently, Oman has signed agreements with Belgium for enhancing partnership for green hydrogen export to the EU[7]. The agreements aimed to assess the readiness of hydrogen production projects in Oman.
- Other countries including Saudi Arabia and South Africa were considered but were not chosen for further analysis. Both have a high dependence on fossil fuels for energy needs. Saudi Arabia has just one hydrogen plant under construction and no plans for e-fuel projects as per the database. On the contrary, South Africa has seven upcoming hydrogen and ammonia plants. However, the country has very few agreements for hydrogen export to the EU. South African population do not have 100% access to grid electricity, which is itself unreliable, and there is a very low percentage of renewables in the grid compared to Namibia. In addition, it has second most longest shipping distance from EU ports. Lastly, both countries have extremely high to medium high water stress levels.

[3] https://www.iea.org/countries
[4] https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS
[5] https://www.wri.org/insights/highest-water-stressed-countries
[6] https://neighbourhood-enlargement.ec.europa.eu/news/eu-and-morocco-launch-first-green-partnership-energy-climate-and-environment-ahead-cop-27-2022-10-18_en
[7] https://fm.gov.om/oman-and-belgium-sign-green-hydrogen-agreements/

1.2 DEMAND TARGETS

There are various demand scenarios presented in European policies and by NGOs such as T&E. We compare the targets for different hydrogen-based energy vectors from EU policy targets including those from the Renewable Energy Directive, RePowerEU, ReFuelEU, and Fuel EU regulations. The following text will highlight various hydrogen targets in the EU:

- **Renewable energy directive** (RED) sets targets for the promotion of the use of energy from renewable sources and is legally binding. RED II raised the EU target for Renewable Energy Sources consumption by 2030 to 32%. Later RED III was released with specific hydrogen and e-fuels targets for industry and transport[8] as shown in Table 1. In February 2023, the Commission proposed to increase the 2030 target for renewables to 45%[9] and in March an agreement was made to increase EU's overall renewable energy consumption to 42.5% by 2030 with an additional 2.5% indicative top up that would allow to reach 45%[10]. It is important to note that renewable fuels of non- biological origins (RFNBO) demand targets given in RED fall far short of the (non-binding) REPowerEU goals.

Table 1 Targets for RFNBOs in 2030 as per RED

Sector	Target for 2030	RFNBO minimum demand (Mt)
Transport	RFNBO must be 1% of the transport consumption[11]	~ 1[12]
Industry	RFNBO must be 42% of hydrogen consumption	3.5

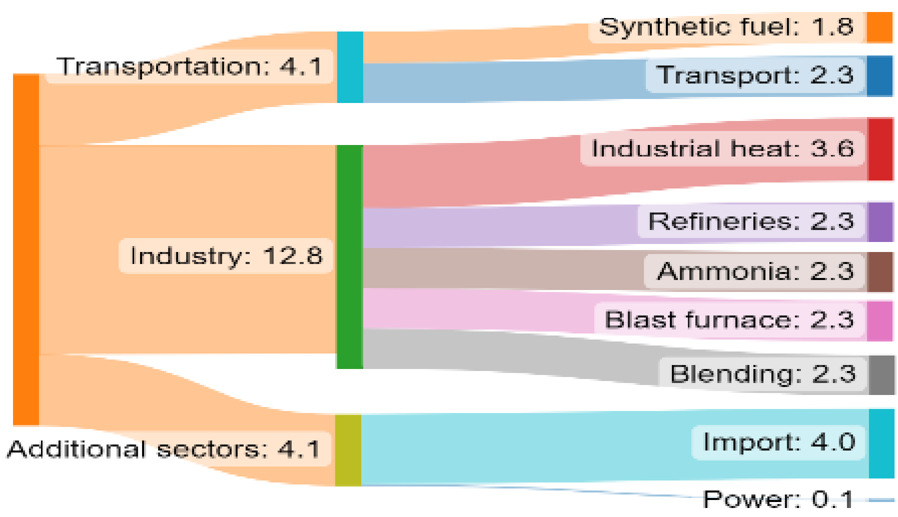
- **REPowerEU** is an ambitious, but non-binding action plan to reduce EU's dependence on Russian fossil fuel. The plan sets a target of 10 Mt domestic renewable and low-carbon hydrogen production and 10 Mt of imports by 2030[13]. Prior to this, Fit for 55 was presented by European Commission with the aim to reduce net greenhouse gas emissions by at least 55% by 2030 and achieve climate neutrality by 2050. The European Commission carried out modelling to calculate the amount of hydrogen required in 2030 as per REPowerEU and Fit-for-55 targets. According to PRIMES modelling the uptake of higher volumes of renewable hydrogen was identified for the Fit-for-55, increasing from 50% to above 75%. The modelling conducted for REPowerEU assumes 10 Mt renewable hydrogen is produced domestically and 6 Mt of renewable hydrogen imported from third countries. The sector-wise targets are shown in Table 2 and the breakdown of demand in different sectors is shown in Figure 1.

Table 2 Hydrogen use by sector in 2030 based on PRIMES modelling

Sector	REPowerEU (Mt)	Fit-for-55 (Mt)
Transportation	4.1	2.8
Industry	11.9	3.9
Power	0.1	-
Imports[14]	4	-

[8] Back in the driving seat? Europe agrees on renewable hydrogen consumption targets | S&P Global (spglobal.com)
[9] https://ec.europa.eu/commission/presscorner/detail/en/IP_23_594
[10] https://www.consilium.europa.eu/en/press/press-releases/2023/03/30/council-and-parliament-reach-provisional-deal-on-renewable-energy-directive/
[11] 1% target is the mandatory target for transport sector and it could reach up to 5.5%
[12] This is adjusted demand as RFNBOs supplied to aviation and shipping are counted as 1.5 times their energy content - https://www.transportenvironment.org/wp-content/uploads/2023/09/RED-III-Fact-sheet-on-RED-targets.pdf 1 to 5
[13] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022SC0230
[14] This import refers to ammonia and other derivative imports

Figure 1 Sector wise breakdown of hydrogen demand in Mt from REPowerEU[15]



- The **Hydrogen Strategy** for Europe was adopted in July 2020, which set a production goal of up to 10 Mt of renewable hydrogen in the EU by 2030[16]. The caveat is that this study comes before RePowerEU and the final Fit for 55 proposals.
- **ReFuelEU Aviation** regulation is proposed by the European Commission as part of Fit-for-55 package. It is a binding tool which aims to increase the use of sustainable aviation fuel (SAF) starting at 2% in 2025 and thereafter minimum share of 6% of SAF[17] starting 2030. It also includes sub-quota for synthetic aviation fuels (or RFNBOs)[18] at 1.2% with that projected synthetic aviation fuels uptake will be about 0.55 million tonne oil equivalent (or 6.3 TWh) in 2030[19].
- **Fuel EU Maritime** regulation is part of Fit-for-55 package, which aims to increase use of sustainable fuels in maritime sector. There is a target of 1% RFNBO in the bunker fuels by 2031 and 2% target as of 2034[20]. Given that the target is 1% only, the amount of all RFNBO will be 3.8 TWh[21].

1.3 AVOIDED AND CONSEQUENTIAL EMISSIONS

This section examines each case study county's avoided emissions should export-focussed hydrogen projects not proceed, and instead the renewables currently intended for hydrogen production are used to decarbonise the local electricity grid. Avoided emissions is defined here as emissions that would no longer be emitted by fossil fuelled power generation which has been displaced by the renewables originally intended for hydrogen production. The ability to avoid these emissions assumes investments can easily be diverted from a hydrogen project to a renewables project, which in practical terms may not be possible, as they form separate investment funds in nearly all cases.

Within each study country, calculations on avoided emissions are subject to a number of assumptions, for example, which fossil-fuelled power generation assets retired in lieu of renewables. For the avoided emissions within the study country, for simplicity, we assume that the renewables will displace fossil fuel electricity generation in the ratio of its current use in that country. We assume that no existing renewables are retired as a consequence of installing new renewables.

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[15] Infographic designed using SankeyMATIC tool
[16] eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301
[17] AG (europa.eu)
[18] Synthetic fuel are sustainable aviation fuels based on non-biologic origin, where the source of energy is not based on crops, or residues or waste, but obtained from renewable electricity.
[19] LexUriServ.do (europa.eu)
[20] AG (europa.eu)
[21] Considering 33 Mtoe fuel oil was used in maritime bunkers in 2019- Heavy fuel oil - production, trade and use - Statistics Explained (europa.eu)

While it is possible to consider the effect of a decision such as this on each country in isolation, in reality, the effects of that change would extend beyond its borders: Europe would still require an equivalent amount of hydrogen, while the consequential CO_2 emissions associated with production in the case study country or elsewhere are global. Therefore the net effect of the decision to redirect renewables to the local grid needs to be considered. This should include not only the in-country avoided emissions but also the consequential emissions of producing the hydrogen elsewhere. Due to the multiple assumptions that would underpin this calculation, it is not covered here, but is recommended for a future study.

The results of this analysis represent a simplified thought experiment of the local impact of countries choosing to prioritise decarbonisation of local electricity. Decisions on whether this would represent a good or bad decision for a country and the global environment would need further analysis including avoided, consequential and marginal emissions, funding options, as well as the effect on jobs, supply chain and balance of payments.

2. SUPPLY CHAIN RISK

Following the Russian invasion of Ukraine, there have been significant global challenges around energy availability and pricing. With the transition to renewable energy, including hydrogen, there is a perceived opportunity to reduce the reliance on foreign energy imports and increase stability in pricing. There is concern in some areas that by continuing to import energy in the form of hydrogen, the EU is continuing to expose itself to energy supply risk. This section aims to explain the risk that hydrogen and its derivatives might face in the coming years. The determination of the supply chain risk for energy (and other commodities) is somewhat complex and in many aspects subjective. Typical factors to be considered include the level of reliance on single sources, the number of sources, the availability of alternatives, the available reserves and the political stability of the supplying countries.

The EU has a calculation for energy supply risk: The N – 1 formula in Annex II of EU Regulation 2017/1938[22] describes the ability of the technical capacity of the LNG import infrastructure to satisfy total gas demand in the calculated area in the event of disruption of the single largest gas infrastructure during a day of exceptionally high gas demand occurring with a statistical probability of once in 20 years. The EU regulation uses this formula to find out supply chain risk from failure of the single largest gas infrastructure (entry point) in the region.

Calculation method of the N – 1 formula

$$N-1\,[\%] = \frac{EP_m + P_m + S_m + LNG_m - I_m}{D_{max}} \times 100,\ N-1 \geq 100\ \%$$

Parameters in the formula include:

D_{max}: Total daily gas demand for the region occurring with a statistical probability of once in 20 years
EP_m: Technical capacity of all border entry points capable of supplying gas to the calculated area
P_m: Maximal technical production capability of all gas production facilities which can be delivered
S_m: Maximal technical storage deliverability of all storage facilities
LNG_m: Maximal technical daily send-out capacities at LNG facility in calculated area
I_m: Technical capacity of the single largest gas infrastructure to supply calculated area

Explanation of the N-1>100 threshold

In the case where the infrastructure is sized to the maximum daily demand, the N-1 threshold requires the sum of the supply points (pipelines, production, storage, and LNG terminals) to be more than twice the maximum daily demand. The idea being that should there be a failure at any one point, that supply can be met. The formula does not imply which supply point should be increased if the N-1 threshold is not met.

This formula was adjusted to find out the supply chain risk when the largest exporting nation fails to supply and was used to carry out the supply risk assessment for natural gas and hydrogen supply. We have adopted this approach to review the supply risk for the entire continent, using the same variables, but applied on a continent-wide basis, replacing the single import terminal variable with a single exporting country. This analysis

[22] https://www.legislation.gov.uk/eur/2017/1938/contents

considers EU27 nations. Thus, the results will identify the supply risk from a single hydrogen exporting country, analogous to the cutting off of Russian natural gas imports. As a value for hydrogen on its own would have limited meaning, we have also applied this methodology to natural gas imports today, including both shipped LNG and gaseous pipeline imports.

Natural gas

The supply chain risk factors are defined for natural gas considering pipeline export and LNG facilities offtake capacity in the EU. The supply chain risk arising from failure of the single largest hydrogen infrastructure was replaced with the single largest natural gas exporting nation. Norway was the largest natural gas supplier in 2022. The formula calculates the impact of failing to secure natural gas supply from the country.

Table 3 Natural gas supply balance sheet for 2022

Factors	Inputs (PJ/day)	Assumptions
D_{max}	79	D_{max} describes the total daily gas demand in the EU on a day of extraordinarily high demand. The annual gas demand in 2010[23] was highest in the last 20 years. For the assessment, quarterly demand[24] from the same year was used to compute daily demand factor.
EP_m	51	EP_m is the total technical physical capacity (per day) of all cross-border interconnector pipelines (IPs) supplying to the EU except Nord Stream. The list of IPs and respective technical capacity is detailed in Appendix 2.
P_m	4	P_m is the total of the maximum technical daily production capacity of all gas production installations in the EU. For assessment, the average daily natural gas production in the EU[25] is used.
S_m	74	S_m is the total maximum daily withdrawal from natural gas storage facilities including depleted reservoirs, aquifers and salt cavern in the EU. The withdrawal rate from different types of storage is detailed in Appendix 2.
LNG_m	15	LNG_m is the total of the largest possible daily offtake capacities of all LNG installations in the EU. This was taken as daily average of the EU's total LNG import capacity of 157 billion cubic metres[26].
I_m	15	I_m is the infrastructure element with the largest supply capacity. For risk assessment, it is taken as daily average of the largest natural gas import from a single country. Import from Norway was 24.4% of the natural gas entering the EU in 2022[27].
N-1	164	

Hydrogen

The factors defined for natural gas were modified to indicate the supply risk for hydrogen supply in the EU. The numbers were based on announcements and targets related to hydrogen production, demand, import and storage. The supply chain risk arising from failure of the single largest hydrogen supply was indicated by failure

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[23] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_supply_statistics#Supply_structure
[24] quarterly_report_on_eu_gas_markets_q4_2012_0.pdf (europa.eu)
[25] This number does not include production of the UK and Norway
[26] Liquefied natural gas (europa.eu)
[27] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Fig5Extra-EU_imports_of_natural_gas.png

of supply from the single largest hydrogen exporting nation. Based on country strategies and official announcements the country is Chile.

Table 4 Hydrogen supply balance sheet for 2030

Factors	Inputs (tonne/day)	Assumptions
D_{max}	18365	D_{max} is the total of the hydrogen demand in the EU. The total demand[28] was taken as daily average of transportation and industry demand as per Fit-for-55[29] in 2030.
EP_m	27397	EP_m is the total technical capacity of border entry point to take hydrogen. The expected hydrogen imports in the EU as per REPowerEU is 10 Mt.
P_m	18082	P_m is the total daily production capacity of hydrogen in the region. About 6.6 Mt of renewable hydrogen is produced domestically in the Fit-for-55 scenario[30].
S_m	82051[31]	S_m is the expected hydrogen storage deliverability in 2030. It is the product of future hydrogen storage demand (80TWh)[32] and average withdrawal rate[33] of underground gas storage facilities.
LNG_m	0	LNG_m and EP_m are combined in EP_m factor as Fit-for-55 doesn't distinguish between different types of import.
I_m	2904	Im is defined as the largest hydrogen import announcement from a country. It was chosen by relying on import targets mentioned in country strategies to find supply risk.
N-1	679	

Both natural gas and hydrogen meet the (N-1) standard and are well above 100%. Natural gas supply risk is high in absence of imports from Norway, as indicated by the low value of risk factor. A higher value for (N-1) for hydrogen is due to high expected import and high hydrogen storage demand in the coming years.

Sensitivity

We have also reviewed sensitivity of the results to the factors for hydrogen supply chain risk. To understand ways in which the resilience of supply of hydrogen could be modified:

1. Doubling of hydrogen demand: There are range of estimates for future hydrogen demand making it difficult to arrive at a definite number for 2030. In such case it is important to consider the implications of any significant increase in hydrogen demand on a given day. If daily demand is double of what is expected in Fit-for-55, the risk factor fall to 339. For increase of 25% and 50% in the daily demand the risk factor will be 543 and 453 respectively.
2. Half of the storage is available: The storage factor in the analysis represents the hydrogen storage demand in 2030. There is a possibility that only a portion storage infrastructure required to fulfil the demand is built.

[28] Sensitivity for 25% and 50% increase in demand is conducted
[29] Based on Fit for 55 - eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022SC0230
[30] Potential measures and investments to reduce dependence on Russian gas by technology, in addition to the Fit-for-55 package - eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022SC0230
[31] This is (80*4%)(TWh)/39(TWh/Mt) Mt where storage withdrawal rate is 4%
[32] Future storage demand is based on Insight on Hydrogen report - A-EW_245_H2_Insights_WEB.pdf (agora-energiewende.de)
[33] Guidehouse GIE - Picturing the value of underground gas storage to the European hydrogen system

If only half the storage infrastructure is built, there would be an increased supply shortage risk. This can be quantified as the value of (N-1) dropping to 445.

3. ENVIRONMENTAL IMPACTS OF RENEWABLES IN COUNTRIES WITH DESERT AREAS

As the EU transitions to Net Zero, the development and implementation of renewable energy technologies will become more prominent in the energy sector. There are many benefits to the use of renewable energy generation, particularly in meeting global carbon emission targets.

The generation from renewable energy power plants is predominantly utilised to meet local and domestic energy demands. In some countries, generation from local renewable energy power plants is used for exporting and trading internationally through power purchase agreements. Countries that aim to utilise and integrate more renewable energy sources in their own energy sector mix have the option of allocating capital and investments towards the development of new renewable energy plants or towards the import of energy generation from renewable plants. The environmental impacts of constructing new renewable energy plants for domestic use will be briefly explored, within the context of countries with desert areas.

3.1 WATER

The quantity of water required for hydrogen production varies depending on several factors including hydrogen type (green vs blue hydrogen), feedwater source, cooling technology and environment. On a stoichiometric basis, green hydrogen from electrolysis requires 9 litres of water per kg of hydrogen produced. This figure does not account for the consumption of raw water, given that electrolysis requires ultrapure water for hydrogen production. Similarly, it fails to account for water used for cooling duty, which often dominates the total water requirements. For evaporative cooling, total raw water requirements might range between 20 and 150 litres per kilogram of hydrogen[34].

In desert countries, water is not an abundant resource. Since pure water is critical for hydrogen production, water will need to be transported to site and water treatment plants will need to be set up[35]. This requires further construction work and investment, that can cause disturbance to local communities and ecosystems.

In most power plant sites, water is needed for auxiliary services (cooling), maintenance and cleaning. In desert countries water in these sorts of quantities is not readily available, and intensive investment will be required to transport water to site for regular usage. Any water spillage will affect the surrounding wildlife and alter the environment.

Using saltwater with desalination as an alternative to fresh water may pose financial and environmental challenges for hydrogen projects[36]. If brine from desalination is disposed into the ocean it may pose risks to aquatic life due to high salt concentrations. It is heavier than seawater if undiluted and it tends to settle towards the bottom suffocating animals on the sea floor. Although plants can use strategies to minimize these impacts such as disposing brine where strong currents help to disperse it or mixing brine into ocean with multiple waste outlets[37].

3.2 WEATHER AND ECOLOGY

Desert countries have optimal weather conditions for setting up solar or wind farm plants, as the desert biome is often windy and sunny. The lack of infrastructure and wispy cloud patterns result in hardly any shading or obstruction from the sun's rays. However, the construction of a solar or wind plant in a desert biome introduces shading on the land, thus changing the existing environment on land and affecting the land biodiversity. The cooler temperatures resulting from shade, can create opportunities for new species to thrive, which can result in competition for water and soil nutrients with existing species. The survival of new flora and fauna, indicates that there is adequate water and moisture content available, which is not particularly characteristic of a desert biome. A 2018 study, modelling the difference in albedo effect caused by solar farms in deserts, showed that

[34] 221114-Arup-Technical-paper-Water-for-Hydrogen-report-FINAL.pdf (h2council.com.au)

[35] https://www.advisian.com/en/global-perspectives/the-importance-of-water-to-the-hydrogen-industry#:~:text=Pure%20water%20is%20critical%20for,making%20it%20seem%20that%20simple.

[36] Scientists produce green hydrogen from seawater - News - The Chemical Engineer

[37] Slaking the World's Thirst with Seawater Dumps Toxic Brine in Oceans - Scientific American

solar of greater than half a GW capacity can in fact trigger a feedback loop due to heat transmitted by dark and large surface of solar panels. Though even the largest planned hydrogen project to date would not have solar sizable enough to cause reverse desertification, the cumulation of solar farms for various energy end use (direct or indirect) could pair with significant environmental benefits[38].

For a solar plant setup, while some areas of the ground surface temperature will become much cooler due to shading, other surfaces will become much hotter due to the excess irradiation that is not absorbed by the solar panels. The black surfaces of solar plants only absorb around 15% of incoming radiation, and the excess is scattered back into the atmosphere, affecting the soil and air temperatures. This can result in the conversion and modification of natural habitats and of weather patterns, which may ultimately influence the regional climate[39].

3.3 SITING AND CONSTRUCTION

Co-location [40] is where multiple generator plants or storage facilities are set up in the same area and share the same grid connection. This allows for an increased flexibility in energy supply, and the maximised use of expensive grid connections and land space, thus avoiding the need for further network expansion investments. By sharing the same network infrastructure on a piece of land, the operational and capital costs are reduced drastically, and the process of set-up and generator online availability is faster.

However, the co-location of renewable assets requires clear certainty and a business framework that ensures the benefits will outweigh any constraints. Co-located plants need to have optimised output profiles that do not strain the network infrastructure, while still generating enough to maximise the revenue of the generation asset. Co-located renewable generators also require the upgrading of network equipment that connects the plant to the grid, to handle the increased loading. This may include replacing or the strengthening of required cables, transformers, and other equipment to satisfy the loading requirements.

Renewable energy plants are usually constructed in areas abundant in renewables, instead of where the produced energy will be used i.e., near consumers. Therefore, the energy produced from power plants needs to be transported through the transmission network to be used by consumers in the distribution network. New power plants thus require transmission infrastructure and grid connection upgrades which is costly.

Construction work will heavily influence the agriculture and soil in surrounding areas; trees will need to be dug up and destroyed in the process of creating long wide roads for construction vehicles and heavy trucks. The renewable energy plant construction can result in soil compaction, change in drainage channels and increased erosion [41].

The construction and installation of a renewable power plant setup will require bulldozing into the land damaging natural layout. It will displace the local fauna and flora and affect their optimal growth patterns as they cannot relocate [42].

Large construction sites also create a lot of noise disturbance for local communities and animals. The natural day cycle is disturbed which changes the way animals and people live [43]. Local residents may not approve of construction work, especially if residents are not directly benefitting from the energy produced by the renewable power plants. The noise and construction work disturbance will become an inconvenience for residents and may require locals to reconsider transportation routes and routines due to construction work blocks. Even though the concept of renewables is appealing due to it being a low-carbon energy source, large power plants can be visually unpleasant for local communities.

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[38] Climate model shows large-scale wind and solar farms in the Sahara increase rain and vegetation | Science
[39] https://theconversation.com/solar-panels-in-sahara-could-boost-renewable-energy-but-damage-the-global-climate-heres-why-153992
[40] https://www.cornwall-insight.com/wp-content/uploads/2022/12/Weightmans-Colocation-Insight-Paper-final.pdf#:~:text=Co%2Dlocation%20is%20where%20multiple,made%20both%20cheaper%20and%20faster
[41] Environmental Impact Of Solar Energy | GreenMatch
[42] How Renewable Energy Impacts Biodiversity - Endangered Species Coalition
[43] https://woodhartgroup.co.uk/news/how-construction-affects-the-environment/

4. STUDY COUNTRY: EGYPT

4.1 INTRODUCTION

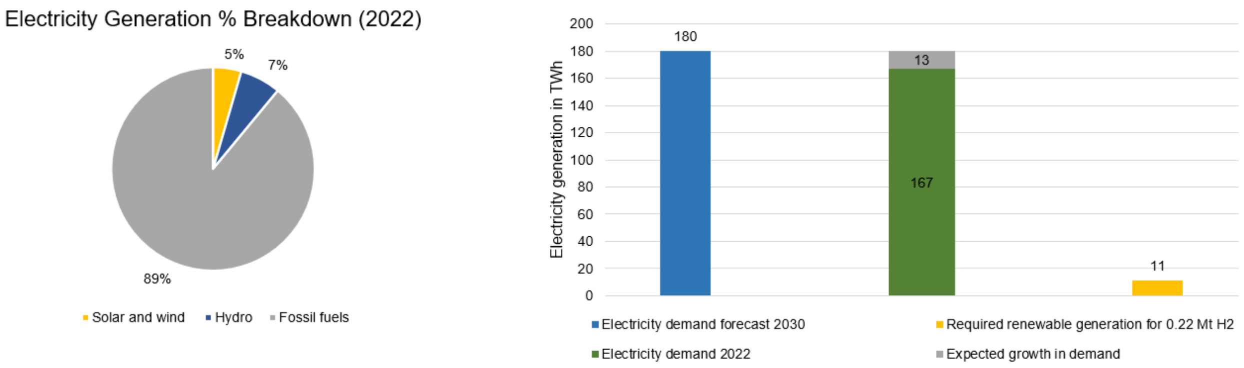
Egypt is quickly becoming recognised in the global low carbon hydrogen sector, driven by ambitious targets and ongoing initiatives. Additionally, negotiations for hydrogen agreements with the EU [44] showcase its commitment to international collaboration. COP27 saw the signing of 8 frameworks for hydrogen projects totalling to $80 billion [45], including a substantial $8 billion factory in the Suez Canal Economic Zone and $3.5 billion projects in Saudi Arabia's Alfanar [46]. With plans to commission 11.62 GW [47] of green hydrogen capacity by 2035, Egypt is establishing itself as a noteworthy contender in the global green hydrogen landscape.

Egypt has formulated a series of proactive policies to accelerate the growth of green hydrogen projects within its borders. The recently drafted law, approved in 2023 [48], aimed at incentivizing eco-friendly initiatives, offers an array of benefits. These include cash investment incentives, equipment VAT exemptions, waived taxes and fees, and customs tax waivers. The law's scope covers various aspects of green hydrogen ventures, spanning production, storage, transportation, and more. It additionally extends its incentives to encompass expansion projects that boost production capacity. To qualify, projects must rely on substantial foreign financing, transfer advanced technology, use domestically manufactured components, and contribute to training and social responsibility initiatives. This comprehensive policy framework shows Egypt's commitment to fostering the green hydrogen industry.

4.2 BACKGROUND & COUNTERFACTUAL

4.2.1 Electricity grid context

Figure 2 Electricity generation mix in Egypt (2022) and comparison of required renewable generation and projected electricity demand (2030)[49,50,51,52]



The size of the electricity grid as per 2022 in Egypt was 167 TWh, with 89% of the supply coming from fossil fuels (predominantly gas and oil), 5% solar and wind and 7% hydro. The emissions intensity of the grid has been reported as 485 gCO_2/kWh[53] and the national access to electricity is 100%[54].

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[44] https://www.dw.com/en/hydrogen-economy-egypt-to-announce-ambitious-h2-strategy/a-63466879

[45] https://www.thenationalnews.com/business/energy/2023/03/14/egypt-to-announce-new-energy-strategy-in-coming-weeks/

[46] https://hydrogen-central.com/cop27-egypt-signs-eight-framework-agreements-hydrogen-projects-including-8-billion-green-hydrogen-factory/

[47] https://www.seetao.com/details/159149.html

[48] https://www.zawya.com/en/projects/industry/egypt-approves-draft-law-to-promote-green-hydrogen-projects-h8j9hjnt

[49] https://www.mees.com/2023/3/24/power-water/egypt-power-consumption-hits-record-167twh-for-2022/a2afbbf0-ca4c-11ed-961e-15a54b525d54

[50] https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Africa/Egypt_Africa_RE_SP.pdf

[51] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Oct/IRENA_Outlook_Egypt_2018_En.pdf

[52] https://www.trade.gov/country-commercial-guides/egypt-electricity-and-renewable-energy

[53] https://ourworldindata.org/grapher/carbon-intensity-electricity?tab=table

[54] https://www.macrotrends.net/countries/EGY/egypt/electricity-access-statistics#:~:text=Access%20to%20electricity%20is%20the,a%200%25%20increase%20from%202020.

By 2030 the electricity system is anticipated to grow to approximately 180 TWh, with a target of 48% coming from renewable sources of electricity based on work by IRENA and The US Trade Administration. Figure 2 highlights the size of renewables development required to meet 0.22 Mt/yr production of hydrogen, the stated amount to be produced in Egypt by 2030. To produce 0.22 Mt/yr of hydrogen, around 7% of the 2022 electricity system would be required in renewables capacity. This could be used to decarbonise the predominantly fossil fuel-based grid, given the required grid infrastructure, highlighting the competing priorities between grid decarbonisation and green hydrogen production. Further discussion in this regard is continued below.

4.2.2 Hydrogen Strategy and Planned Projects

Figure 3 Comparison of 2030 targets in H2 strategy, planned projects and expected EU exports

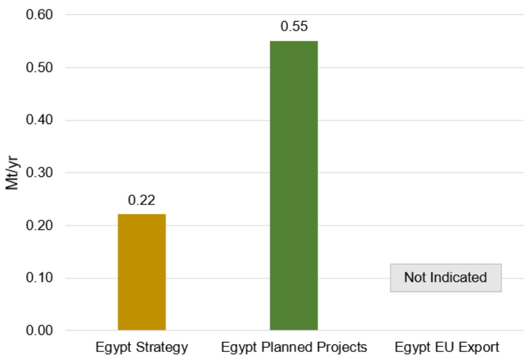

Figure 3 shows the Egypt hydrogen production strategy for 2030 and the planned projects as per the International Energy Agency (IEA) hydrogen project database and other available data. The planned projects already exceed the volume in the strategy, though there is no data on the expected volume to be exported to Europe.

4.2.1 Avoided and Consequential Emissions

The table below summarises the potentially avoided emissions if renewables originally intended for green hydrogen to be exported to the EU (11 TWh) were reprioritized for grid decarbonisation.

Table 5 Summary of avoided emissions - Egypt

Avoided Emissions ($MtCO_{2eq}$/yr)	5.3
Total grid emissions in 2022 ($MtCO_{2eq}$/yr)	71.4
Potential Decrease in Electricity Emissions (%)	7.4

By not producing hydrogen, Egyptian grid emissions would decrease by ~7%, which, while beneficial, is not transformational. Although there would be emissions avoided in Egypt it is likely there will be consequential emissions elsewhere to meet the demand for hydrogen in the EU and elsewhere. These may be higher or lower than the avoided emissions in Egypt, depending on several factors. This scenario assumes investments can easily be diverted from a hydrogen project to a renewables project, which in practical terms may not be possible, as they form separate investment funds in nearly all cases. This scenario also does not consider the potential for greater penetration of renewables in Egypt as a function of improved local supply chain following development of the hydrogen export-focussed renewables.

4.2.2 Environmental, Social and Economic Factors

There are plans to install a pipeline connecting Gulf states, through Egypt, to supply the EU with a target of 2.5 Mt/yr of low carbon hydrogen in the 2030s[55]. There is a risk of various environmental impacts in the form

[55] https://afry.com/sites/default/files/2023-06/3355_afry_and_rina_joint_discussion_paper_hydrogen_pipeline_from_the_gulf_to_europe_use_case_and_feasibility_considerations_june_2023.pdf

of embodied emissions for the infrastructure that will be installed, disrupted ecosystems and strain on services such as water. These impacts need to be carefully considered in the implementation of such a project.

The Climate Action Tracker, an independent scientific project making use of the MAGICC climate model, tracks climate action by various governments against the Paris Agreement which aims to keep warming well below 2°C[56]. Based on data by the Climate Action Tracker, if all countries were to adopt Egypt's policies, and action it would be aligned with warming between 2°C and 3°C[57]. Some renewables development has been achieved in Egypt; however, the current projects are not significant in comparison to the fossil fuel generation capacity. Given that the production of green hydrogen will require significant renewables rollout this shows a clear competition with decarbonising the grid and driving progress according to the Paris Agreement.

Egypt is a relatively equal country in terms of wealth distribution with a gini coefficient[58] of 32[59] (compared to Belgium with a coefficient of 26, where lower is better)[60]. Unemployment levels are around average for the African continent at about 7%[61]. This said, the World Bank has reported poverty levels (individuals earning less than $3.65 per day) of 17.6% and many Egyptians are reported to be at risk of falling under the poverty line[62][63]. These factors are useful to note because new industries such as the green/low carbon hydrogen economy could present an opportunity to improve the socio-economic standing of the producing country's communities by stimulating quality job creation and local development. With the current extractive industries such as fossil fuels, there is often little local benefit to exporting countries. If hydrogen is to play its part in the just transition, the benefits and opportunities of hydrogen production should ideally be more fairly shared between domestic production and likely international funders or developers.

4.3 FURTHER COUNTRY DETAILS

4.3.1 Projects powered by the grid

To identify projects that would rely on power from the grid, the BNEF and IEA databases were researched and analysed. There are no announced projects in Egypt at feasibility stage or advanced that plan to use grid power.

4.3.1 Water analysis

Egypt's location in the north-eastern corner of the African continent borders the Mediterranean and the Red Sea[64]. Within its territories, it contains the Northern Interior Basin, Nile Basin, Mediterranean Coast Basin and Northeast Coast Basin. The Nile River comprises almost the entire water supply and renewable water resource for the country[65]. For the populations living within the desert areas, the primary source of water is groundwater systems. The Nile aquifer accounts for approximately 85% of total groundwater abstraction in Egypt. The supply of water by the Nile River is largely controlled by the High Aswan Dam. There is also a network of waterways, many of which branch from the Nile River. Most of surface water resources supply the agriculture sector. From the total water usage, over 61% is used in agriculture sector, 11% in municipalities, 5% in in industrial sector and remaining in other applications[66].

Much of the drainage water which occurs in Upper Egypt flows back into the Nile. Some is also captured to be reused in agriculture. Reuse projects are not uncommon, particularly south of the Delta. Of the total amount of municipal wastewater, approximately over 90% is collected and 57% of it is treated, based on 2010 data. Sea water desalination systems exist and are concentrated primarily amongst coastal regions where

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[56] https://climateactiontracker.org/about/

[57] https://climateactiontracker.org/countries/egypt/policies-action/

[58] **The Gini coefficient is a measure of statistical dispersion intended to represent the income inequality within a nation or a social group (0 = low levels of inequality, 100 = high levels of inequality)**

[59] https://www.statista.com/outlook/co/socioeconomic-indicators/economic-inequality/egypt#poverty-share

[60] https://www.worldeconomics.com/Inequality/Gini-Coefficient/Oman.aspx#:~:text=Perfect%20equality%20means%20a%20country's,most%20recently%20measured%20in%202019.

[61] https://data.worldbank.org/indicator/SL.UEM.TOTL.ZS?locations=EG

[62] https://databankfiles.worldbank.org/public/ddpext_download/poverty/987B9C90-CB9F-4D93-AE8C-750588BF00QA/current/Global_POVEQ_EGY.pdf

[63] https://www.theguardian.com/global-development/2023/may/08/inflation-imf-austerity-and-grandiose-military-plans-edge-more-egyptians-into-poverty

[64] *I9729EN.pdf (fao.org)*

[65] Past and future trends of Egypt's water consumption and its sources | Nature Communications

[66] Water Use in Egypt - Fanack Water

availability of surface and groundwater are not feasible. At present, there are 90 operational desalination plants with 850,000 m^3 of daily intake capacity[67].

Egypt's forecasted water security issues stem from several avenues[68]:

- Saltwater intrusion due to groundwater overextraction and large reuse of drainage water thereby increasing the salt load in certain systems.
- Most of the country receives very low rainfall, a mechanism which creates concern when considering climate change induced warming, therefore further evaporation.
- The expansion of the urban population placing stress on an already highly extracted system and exacerbating existing issues. However, Egypt has unconventional water supply options, particularly with water desalination.
- The Ethiopian Renaissance Dam may cause issues for other users of the Nile including Egypt.

According to the United Nations, Egypt is facing and annual water deficient and is estimated to be categorised as water scarce by 2025[69], and with the population of 109 million projected to grow significantly in the coming decades, the demand for water in the region will grow. This may call into question the expansion of electrolyser capacity and the use of water in a process to produce hydrogen.

4.3.2 Carbon feedstock

Egypt could potentially recycle industrial emissions for e-fuels projects given the country is a major emitter of carbon dioxide. In 2020, Egypt emitted over 210 Mt CO_2 equivalent,[70] the majority of which resulted from point sources such as electricity and heat production, followed by transport and manufacturing industries, and construction[71]. It is, however, worth noting that the European Commission defined so-called "avoided emissions"[72] for captured CO_2 to be used in e-fuel production. It stipulates that emissions captured from the combustion of non-sustainable fuels for electricity production will only fall under avoided emissions up to 2035, while emissions from other uses of non-sustainable fuels should be considered "avoided emissions" up to 2040. Emissions from electricity production will become ineligible from 2036. Industrial emissions may only be used as a feedstock up to 2040 (depending on the source) if a carbon price has already been paid for these emissions.

The availability of biogenic sources is limited in Egypt. The country is lightly forested with less than 1% of forest cover[73], and biomass is not used for electricity generation. In the total energy mix, biomass makes up a very modest portion[74]. Therefore, Egypt will need to rely on direct air carbon capture and industrial emissions for the sourcing of renewable carbon feedstock in future.

Sourcing the carbon for e-fuel production

European Commission has defined "avoided emissions" for captured CO_2 to be used in e-fuel production. It stipulates that emissions captured from the combustion of non-sustainable fuels for electricity production will only fall under avoided emissions up to 2035, while emissions from other uses of non-sustainable fuels should be considered "avoided emissions" up to 2040. Emissions from electricity production will become ineligible from 2036. Industrial emissions may only be used as a feedstock up to 2040 (depending on the source) if a carbon price has already been paid for these emissions.

4.3.3 Cumulative land and water requirements for planned projects that have an EU export focus in Egypt

As previously mentioned, the construction and operation of export scale hydrogen plants with co-located renewables can be considerable. In addition, water requirements for large scale electrolysis are extensive, but largely variable dependent on the water source and electrolyser technology. Ricardo's estimates for the total

[67] Water desalination in Egypt; literature review and assessment - ScienceDirect
[68] Water resources in Egypt and their challenges, Lake Nasser case study - ScienceDirect
[69] 'No other alternative': Egypt worries as climate change, dam project threaten Nile water supply - ABC News (go.com)
[70] https://data.worldbank.org/indicator/EN.ATM.CO2E.KT?locations=EG
[71] https://data.worldbank.org/indicator/EN.CO2.ETOT.ZS?locations=EG
[72] https://energy.ec.europa.eu/system/files/2023-02/C_2023_1086_1_EN_ACT_part1_v5.pdf
[73] https://www.fao.org/forestry/country/57478/en/egy/#:~:text=Egypt%20is%20lightly%20forested%2C%20with,strain%20on%20the%20delicate%20ecosystem.
[74] https://www.iea.org/countries/egypt

land and water requirements in Egypt, accounting only for projects included in the analysis of this study that have an EU export focus, are below:

Table 6 Total land and water requirements for planned projects that have an EU export focus

Supply Scenario	Km^2 required		Water Required Mt/y
100% Solar + Electrolysis plant	81.11	Equivalent to 7,510 football fields	2.2-3.3
100% Wind + Electrolysis plant	558.19	Equivalent to 51,654 football fields	

4.4 MASDAR HASSAN ALLAM GREEN HYDROGEN PLANT

Egypt's drive towards a hydrogen economy was bolstered by the signing of framework agreements to support the country becoming a hub for hydrogen production, with aims of securing 5% of the global market by 2040[75]. There are plans for development of two green hydrogen production plants in Egypt, one in the Suez Canal Economic Zone (SCZONE) and the other on the Mediterranean, with 2 GWe electrolysis facility in SCZONE set to begin operations by 2026 and further plans to extend electrolyser capacity in both facilities up to 4 GWe by 2030[76] to produce 0.48 Mt green hydrogen per year, which can produce 2.3 Mt per year of green ammonia. Egypt's proximity to markets where demand for green hydrogen is expected to grow the most, including Europe via the Mediterranean provides robust opportunity for export[4], however barriers to the development of a hydrogen economy include freshwater scarcity, the distance between optimum green hydrogen production sites, and the need to export through sea ports[5].

Land use of the plant and co-located renewables: Masdar Hassan Allam green hydrogen will be a 4 GWe capacity hydrogen plant by 2030. It is the largest plant in the country planning to export hydrogen to the EU. It is expected to be located in the Suez Canal Economic Zone and powered by a combination of solar and wind energy. Hydrogen plant footprint including supporting equipment[77] will be 0.54 km^2. There is absence of data on the size of the solar and wind plant. Assuming 10 GW solar and 5 GW[78] wind is required to power the electrolyser, the total footprint[79] would be approximately 6683 km^2.

Social & natural value:

The unique geographical position of the Suez Canal makes it a vital interface for worldwide trade and of special importance to the world as well as Egypt. The SCZONE is an area surrounding the canal that was created in 2015 to capitalise on the large volumes of trade passing through the Suez Canal, which handles 12% of global trade annually. The SCZONE extends over 461 km^2 and comprises logistics and economic zones around the canal, placing Egypt at the centre of global trade and offering logistics that facilitates a trade gateway. The SCZONE is also of strategic importance to Egypt's economy with attractive investment and employment opportunities having already created 100,000 jobs with aims to increase this to 1 million by 2030[80].

[75] Egypt signs framework deals in bid to launch hydrogen industry | Reuters

[76] Masdar-led consortium signs deal to develop Suez Canal green hydrogen project | Reuters

[77] Assuming space requirement for hydrogen production facility along with balance of plant is 136m^2/MW electrolysis capacity- Hydrogen supply chain evidence base (publishing.service.gov.uk)

[78] Considering half of the required electricity is generated from solar power plant and other half from wind power plant with capacity factor of 20% and 40% respectively.

[79] Footprint for wind energy plant is 85 acres/MW and solar energy plant is 123 acres/MW- Calculating Solar Energy's Land-Use Footprint (renewableenergyworld.com)

[80] The Modern Trading Hub at the Center of the World's Most Historic Waterway (bloomberg.com)

The Nile River is the primary water source of Egypt, and also of significant economic benefit to the region supporting agriculture and fishing[81]. The Nile flows into the Mediterranean Sea where the Nile delta is situated, which ranks among the world's most fertile farming areas and is surrounded by a highly arid environment[82].

Analysis:

With the rollout of infrastructure required to achieve a green hydrogen economy, particularly with a focus on fuel bunkering using green hydrogen and its derivatives in the SCZONE, the canal is liable to be widened and deepened when required to cope with the development in ship sizes and tonnages[83]. With an increase in invasive marine species entering Mediterranean waters through the Suez Canal[84], further expansion to accommodate new green infrastructure may exacerbate this problem.

5. STUDY COUNTRY: OMAN

5.1 INTRODUCTION

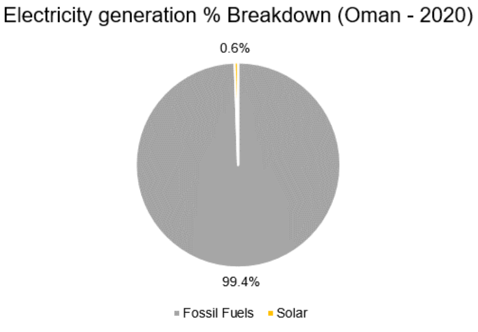
Leveraging its potential rich renewable energy resources and expansive land availability, the country is positioning itself to become a significant producer of renewable hydrogen. Oman aims to annually produce 1 million tonnes of green hydrogen by 2030 and over 8.5 million tonnes by 2050. Its strategy centres on green hydrogen extracted from desalinated seawater using renewable electricity, supported by a dedicated entity, Hydrogen Oman (HYDROM), and facilitated through land allocation and project auctions. Furthermore, Oman is envisaging substantial investments in renewable power generation and infrastructure[85].

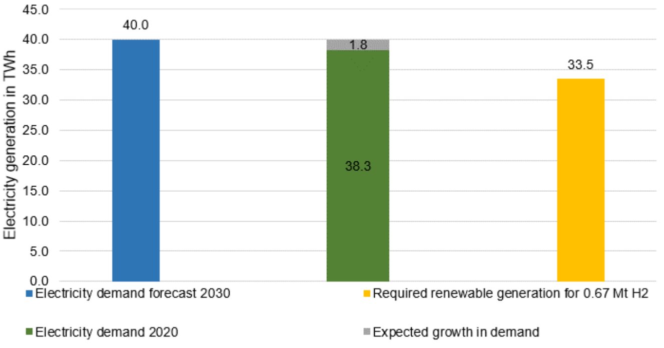
To support these projects Oman government has created a state-owned company, Hydrogen Development Oman (HDO) as a subsidiary of Energy Development Oman. Moreover, as of June 2022, to promote Oman as a centre of production and export of green hydrogen, the Ministry of Energy and Minerals has set up a think tank[86]. Regulation and policies specific to supporting green hydrogen in Oman are expected to be set up in 2023[87].

5.2 BACKGROUND & COUNTERFACTUAL

5.2.1 Electricity Grid Context

Figure 4 Electricity generation mix in Oman (2020) and comparison of required renewable generation and projected electricity demand (2030)[888990]





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[81] Nile - Wikipedia

[82] Delta Alliance - Nile Delta (delta-alliance.org)

[83] SCA - Why Suez Canal?

[84] For the Mediterranean, the Suez is a wormhole bringing in alien invaders (mongabay.com)

[85] https://gh2.org/countries/oman#:~:text=Oman%20plans%20to%20produce%201%20million%20tonnes%20of,10%20GW%20by%20the%20end%20of%20the%20decade.

[86] https://gh2.org/countries/oman

[87] https://www.omanobserver.om/article/1129434/business/supporting-green-hydrogen-regulation-in-oman-to-be-issued-in-q1-2023

[88] https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Middle%20East/Oman_Middle%20East_RE_SP.pdf

[89] https://www.statista.com/statistics/958457/oman-estimated-renewable-energy-capacity-by-type/

[90] https://www.trade.gov/market-intelligence/omans-renewable-energy-projects

In 2020 the electricity supplied by the grid in Oman was about 38 TWh, with 99% of this coming from fossil fuel sources (mainly oil and natural gas) as seen in the figure above. Because the grid is predominantly supplied with fossil fuel derived electricity, the emissions intensity is 488 gCO_2/kWh[91]. Oman has 100% electricity access being reported[92]. Electricity demand is expected to grow to approximately 40 TWh by 2030, excluding hydrogen production. The renewables contribution by 2030, according to plans by the government, should be 30%.

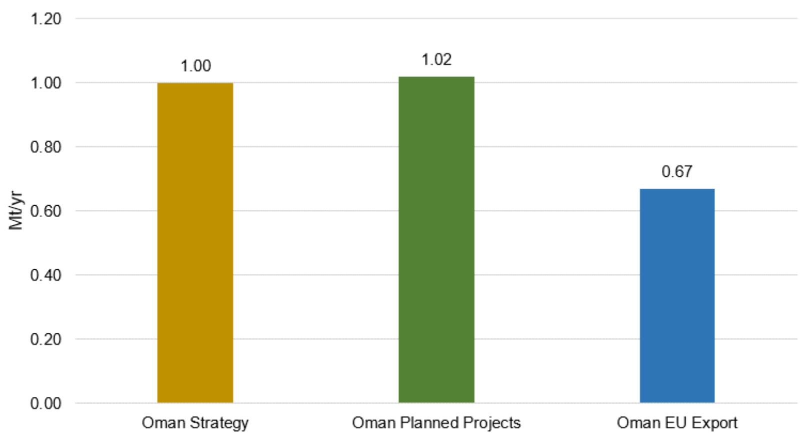
If Oman were to only develop renewables for hydrogen production as 2030 approaches, there would be a conflict with the decarbonisation of the grid as the renewables required for green hydrogen exports could decarbonise 87% of the electricity system as per 2020 (please see Figure 4).

5.2.2 Hydrogen Strategy and Planned Projects

Based on Figure 4, it can be seen that if Oman were to produce 0.67 Mt/yr of hydrogen (as per the expected export amount predicted by the IEA, reflected in the chart below) and assuming a 50 kWh/kg electrolyser efficiency, this would require 4.8 TWh less electricity than the 2020 electricity supply and 6.5 TWh less than the forecasted 2030 supply. This indicates the sheer scale of renewables capacity expansion that will be required and the competition between decarbonising the grid or producing green hydrogen.

The hydrogen strategy of Oman anticipates 1 Mt/yr production of hydrogen by 2030 whilst planned projects past the feasibility stage will have a cumulative production of 1.02 Mt/yr.

Figure 5 Comparison of 2030 targets in H2 strategy, planned projects and expected EU exports



5.2.3 Avoided and Consequential Emissions

The table below summarises the potentially avoided emissions if renewables originally intended for green hydrogen to be exported to the EU (33.5 TWh) were reprioritized for grid decarbonisation.

Table 7 Summary of avoided emissions – Oman

Avoided Emissions ($MtCO_{2eq}/yr$)	15.1
Total grid emissions in 2022 ($MtCO_{2eq}/yr$)	17.1
Potential Decrease in Electricity Emissions (%)	88

By not producing hydrogen for export to the EU, grid emissions in Oman would decrease by ~88% which could be transformational with regards to decarbonisation. The reprioritisation of renewables is contingent on the redirection of investments from hydrogen to renewables, as mentioned previously. Although there would be emissions avoided in Oman it is likely there will be consequential emissions elsewhere to meet the demand

[91] https://ourworldindata.org/grapher/carbon-intensity-electricity?tab=table

[92]https://tradingeconomics.com/oman/access-to-electricity-percent-of-population-wb-data.html#:~:text=Access%20to%20electricity%20(%25%20of%20population)%20in%20Oman%20was%20reported,compiled%20from%20officially%20recognized%20sources.

for hydrogen in the EU and elsewhere. These may be higher or lower than the avoided emissions in Oman, depending on several factors.

5.2.4 Environmental, Social and Economic Factors

Scope 2 emissions should be expected if hydrogen is to be exported from Oman as this will be likely by means of cargo ship. Salalah to Rotterdam by cargo is approximately 10,000 km and for 0.67 Mt/yr of hydrogen exported, the shipping of the H_2 could amount to around 141,000 tCO_{2eq}/year, more than 30,800 typical passenger cars in one year (please see the Appendix for calculations). These emissions will be unabated until the shipping industry manages to decarbonise operations, which will likely be after 2030. Further unabated emissions would be related to the transport that may be required to the demand point within the EU.

The Paris Agreement came into effect in Oman only in 2020, meaning there is not significant data tracking the progress of the country based on nationally determined contributions (NDCs). Oman reached peak emissions in 2019 and has seen a decline since then alongside a strengthening of the NDC through clearer targets and policies[93]. This said, given Oman's heavy reliance on fossil fuels for domestic use and export, significant progress needs to be made to see progress toward decarbonisation.

Oman is a relatively equal country in terms of wealth distribution, with a gini coefficient[94] of 32 (compared to Belgium with a coefficient of 26). The unemployment rate is lower than many developed nations, with an unemployment rate of around 2%[95]. However, it is reported that 10.1% of Oman's population lives in poverty[96]. In order to further improve on these economic indicators, as well as increase ambition as per the Paris Accord, hydrogen developments should ideally be planned in a manner that stimulates local economic development and involves local people in the creation of a hydrogen economy.

5.3 FURTHER COUNTRY DETAILS

5.3.1 Projects powered by the grid

From data collected and analysed as part of this study, there are no announced projects in Oman at feasibility stage or advanced that plan to use grid power.

5.3.2 Water analysis

Oman is extremely hot country, with very little rain and they recently recorded the world's hottest low temperature ever because of climate change impacts. Climate experts say that Oman, especially its coastal areas, is at risk due to climate change leading to rising sea levels, salty water seeping in, and stronger tropical storms threatening people and important buildings[97].

Of the total available water in Oman, approximately 87% is sourced from surface and groundwater, whilst the remaining amount derives from seawater desalination and treated wastewater. Over 90% of the population in the country has access to clean water[98]. As Oman is in the south-eastern corner of the Arabian Peninsula it is bordered by the Gulf of Oman and the Arabian Sea. This has made desalination a familiar option for water availability, particularly for many of the major coastal cities or where natural water availability is low. Observing 2018 data, of the total water use in Oman, 83% was directed toward agriculture, comprising 95% of groundwater use, whilst the remaining quantities went toward industrial activity (13%) and municipal use (5%)[99]. This current system creates a replenishment deficit in many areas. Over-abstraction has also resulted in seawater intrusion and compromised water quality. The arid trait of this region of the world, alongside climate change exacerbate the water stress. Refinement of irrigation and drainage techniques are being considered to aid mitigation[100].

93 https://www.climatewatchdata.org/countries/OMN?end_year=2020&start_year=1990#climate-enhancements
94 https://www.confiduss.com/en/jurisdictions/oman/
95 https://tradingeconomics.com/oman/unemployment-rate
96 https://www.unescwa.org/publications/policy-reforms-lift-three-million-gcc-nationals-poverty
97 Second NDC Report Oman.pdf (unfccc.int)
98 Oman Clean Water Access 2000-2023 | MacroTrends
99 *AQUASTAT Country profile – Oman (fao.org)*
100 *Spatiotemporal mapping of groundwater salinity in Al-Batinah, Oman - ScienceDirect*

Oman's water strategy actively support the use of desalinated seawater to secure municipal water supply[10197] and similar approach is expected to be used to meet the water requirement for hydrogen projects[102]. Green hydrogen produced using such method have lesser water consumption when compared to the fossil fuels based primary energy production, power generation and irrigated agricultural sector. In addition, introducing desalination process increases the total energy requirement in green hydrogen production, but it is insignificant compared to energy required to power the electrolyser[103].

5.3.3 Carbon feedstock

Currently, there are no carbon-based e-fuel projects in the pipeline besides green ammonia projects in Oman. Oman could potentially utilise its industrial sector for the production of e-fuels. The country emitted over 71 Mt CO_2 equivalent emissions in 2020[104], with highest contribution from the manufacturing industry, electricity and heat production, and a small contribution from transportation and other sectors[105]. Oman's main industry is centred around the oil sector, cement, steel, etc. However, Oman can rely on industrial emissions only where a carbon price has already been paid for those emissions until 2040 as highlighted in 4.3.2.

There appears to be minimal potential for biogenic carbon sources in Oman. It has extremely low biomass potential[106], thus, does not have any contribution from biomass to electricity production and the total energy supply in 2020. This indicates that biomass accessibility and its sourcing could be particularly difficult in Oman. Therefore, any sources of carbon feedstock are expected to be direct air capture and industrial emissions including cement and steel industry.

5.3.4 Cumulative land and water requirements for planned projects that have an EU export focus in Oman

The construction and operation of export scale hydrogen plants with co-located renewables can be considerable. In addition, water requirements for large scale electrolysis are extensive, but largely variable dependent on the water source and electrolyser technology. Ricardo's estimates for the total land and water requirements in Oman, accounting only for projects included in the analysis of this study that have an EU export focus, are below:

Table 8 Total land and water requirements for planned projects that have an EU export focus

Supply Scenario	Km² required		Water Required Mt/y
100% Solar + Electrolysis plant	617.38	Equivalent to 57,165 football fields	13.4-20.10
100% Wind + Electrolysis plant	2833.32	Equivalent to 262,344 football fields	

101 iqpc.com/media/8328/11507.pdf
102 Oman's Hydrom Opens for 2nd Auction, Driving Green Hydrogen Production for Net Zero (carboncredits.com)
103 Does the Green Hydrogen Economy Have a Water Problem? | ACS Energy Letters
104 https://data.worldbank.org/indicator/EN.ATM.CO2E.KT?locations=OM
105 https://data.worldbank.org/indicator/EN.CO2.TRAN.ZS?locations=OM
106 Oman_Middle East_RE_SP.pdf (irena.org)

5.4 GREEN ENERGY OMAN INTEGRATED GREEN FUELS PROJECT

Green Energy Oman (GEO) is a proposed clean fuels hub sited in the southern region of Oman. It is claimed by the developers to be one of the most promising clean fuel hubs in the world and as such will be the focus of a case study to analyse the physical space for such a project as well as the social and natural value of the surrounding area.

Figure 6 Renewable energy study areas and production site for the GEO project

Land use: The coastal site will be located in the south of Duqm city[107] present in the Al Wusta Governorate. The proposed site area will be up to 6500 km^2 and has strong wind and solar resources, combined with a low population density making it an ideal location for such a large-scale project. The upstream land will accommodate wind turbines and solar panels, with a green fuel hub for production, storage, and export via shipping vessels in the downstream area[108].

Hydrogen and renewable plant: The GEO green fuels hub will be a 25 GW wind and solar green fuels facility comprised of 1,800 turbines, and 20 million solar panels to be installed over a 10-year period and will utilise a desalination plant. The project will be able to overproduce fresh water to supply local communities although numbers are not known. Desalination plants such as this are a potential community benefit that would not otherwise happen without the hydrogen plant. Once operational the facility is planned to produce 1.8 million tonnes of green hydrogen and 10 million tonnes of green ammonia per annum.

Social & natural value: Duqm is a nascent city which was a small fishing settlement prior to 2011, but projections suggest a population of over 100,000 in the near future[109]. Oman is historically dependent on oil and gas, a dependency that it has struggled to change. In the long term, oil and gas reserves will eventually run out, so the country is trying to diversify its economy by developing tourism, transport, and real estate. To this end, the sultanate of Oman intends to create one of the most important ports in the Middle East, leveraging the strategic position of the Duqm area on the Arabian sea[110].

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[107] https://www.ammoniaenergy.org/articles/oman-green-ammonia-supergiant-takes-shape/
[108] Green Energy Oman | GEO
[109] 'Five years ago there was nothing': inside Duqm, the city rising from the sand | Cities | The Guardian
[110] The Duqm refinery project | Saipem

Analysis: The potential locations of the project as per the GEO study area were analysed using the satellite images and none of them had presence of settlements. Central Oman has vast stretches of gravelly desert with very little vegetation[111]. Thus, any disruption in terms of land clearing would be minimal. However, consideration should be given to the impact of anthropogenic activities in the desert as any local ecosystems will have evolved in a very sustained and undisturbed environment.

Geo study is located near Haima (or Hayma) district and the desert region have few tribal settlements. An isolated and nomadic tribe named Harasis is found in central desert of Oman with population of around 2400[112]. Although, there are 5000 people in total, some people have built urban settlements in city of Haima.

6. STUDY COUNTRY: NORWAY

6.1 INTRODUCTION

Norway, aiming to reduce emissions by 50-55% by 2030 and 90-95% by 2050[113], is prioritising hydrogen for emissions reduction, particularly in transport and industry. Backed by a NOK 3.6 billion Green Package and a Norwegian Hydrogen Strategy[114], institutions like The Norwegian Research Council, Innovation Norway, and Enova are driving research and development, focusing on cost-effective hydrogen production, transportation, and storage. The strategy outlines two low-carbon hydrogen production methods: natural gas reforming with carbon capture and electrolysis. Norway's Energy21 Strategy and incentives like VAT exemptions for hydrogen vehicles underscore its hydrogen commitment.

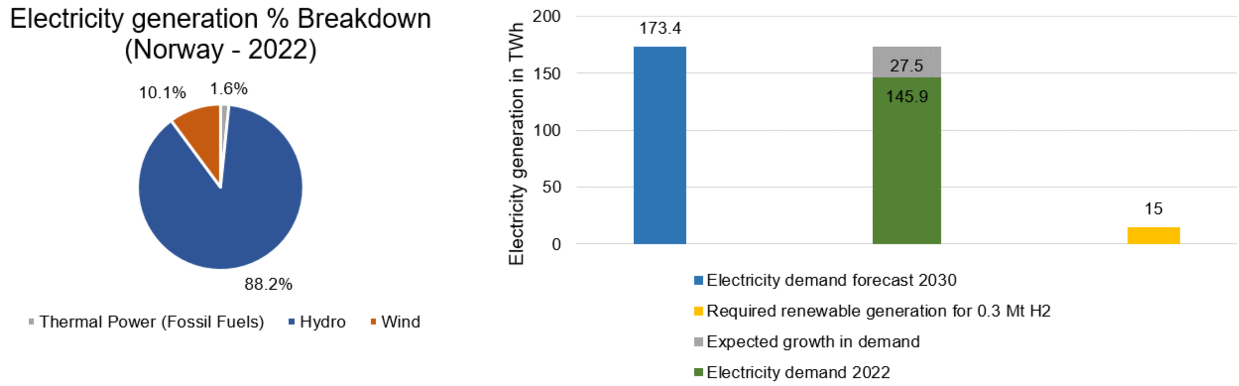
Norway recognises the importance of setting up comprehensive regulations that guarantee the secure handling and application of hydrogen technologies. These regulations encompass aspects such as risk assessments, safety distances, and adherence to recognised norms for hydrogen plants. The Norwegian Directorate for Civil Protection (DSB) assumes a pivotal role in overseeing hydrogen. The government's commitment extends to personnel training for safe hydrogen handling. Norway is actively involved in international standardisation efforts, particularly evident through its contributions to the International Maritime Organization (IMO), where it played a leading role in developing the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (the IGF Code). Collaborative partnerships between regulatory bodies, industry players, and organisations are essential to ensure the safe application of hydrogen[115].

[111] Wildlife of Oman - Wikipedia
[112] https://joshuaproject.net/people_groups/print/12064/MU
[113] Executive summary – Norway 2022 – Analysis - IEA
[114] Norway announces Norwegian Hydrogen Strategy – Hydrogen East
[115] The Norwegian Government's hydrogen strategy - Climate Change Laws of the World (climate-laws.org)

6.2 BACKGROUND & COUNTERFACTUAL

6.2.1 Electricity Grid Context

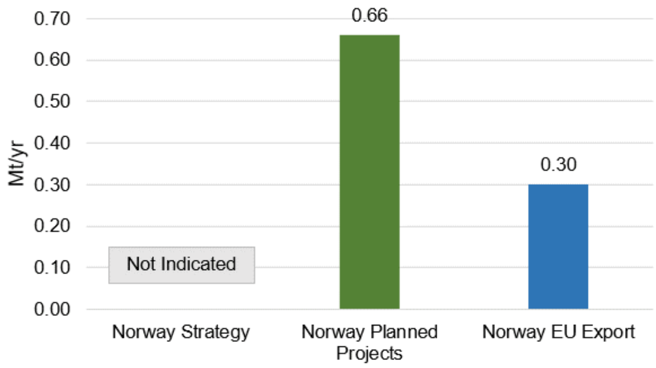
Figure 7 Electricity generation mix in Norway (2022) and comparison of required renewable generation and projected electricity demand (2030)[116][117]



The Norwegian electricity mix is made up of predominantly renewables with 88% coming from hydro, 10% from wind and the remaining 2% from fossil fuels as of 2022. Given this, the grid intensity is 29 gCO_2/kWh which is one of the lowest in the world. Not only is the electricity predominantly renewable in the jurisdiction but the nation also has 100% access to electricity. According to the Montel Group, electricity demand is forecasted to increase from around 146 TWh to 173 TWh by 2030, some of which may be for hydrogen production, though this is unclear. To get a sense of scale the figure above compares the electricity required to produce 0.3 Mt/yr of hydrogen (expected EU export) with the electricity system in 2022 and 2030. This highlights that the electricity supply would need to be increased by about 10% compared to 2022 data to achieve 0.3 Mt/yr production. In practice this would require significant wind, or hydro, development given the renewable resources available to Norway. Further information on Norway's ambition with regards to hydrogen is highlighted in the following section.

6.2.2 Hydrogen Strategy and Planned Projects

Figure 8 Comparison of 2030 targets in H_2 strategy, planned projects and expected EU exports[118]



Although the Norwegian government has set out policy objectives and priorities with regards to the hydrogen economy there has been little mention of numerical targets in their strategy, as shown in the figure above[119]. Based on the research conducted it can be ascertained that projects of up to 0.66 Mt/yr have been planned so

[116] https://www.ssb.no/en/energi-og-industri/energi/statistikk/elektrisitet

[117] https://montelgroup.com/updates-and-insights/expected-consumption-growth-in-the-nordpool-areas-2030-and-beyond

[118] EU Export: https://www.hydrogeninsight.com/production/blue-hydrogen-from-norway-unlikely-to-make-much-impact-on-european-clean-h2-market-says-dnv/2-1-1361146

[119] https://www.regjeringen.no/contentassets/40026db2148e41eda8e3792d259efb6b/y-0127e.pdf

far and 0.3 Mt/yr projected to be exported to the EU by 2030. This will imply 10-20% of the electricity system in additional generation based on 2022 numbers. There will be considerations required for onshore and offshore wind expansion or hydro development given the location. It must be noted that given Norway's existing oil and gas facilities in the North Sea it is possible that blue hydrogen will play a role in the hydrogen economy. Until CCUS and DAC are viable technologies any fossil derived hydrogen will be significantly emissions intensive. Further, lock-in to fossil fuel technologies and inefficiencies in the supply chain leading to leaks of CO_2 are two notable drawbacks to pursuing blue hydrogen.

6.2.3 Avoided and Consequential Emissions

The table below summarises the potentially avoided emissions if renewables originally intended for green hydrogen to be exported to the EU (15 TWh) were reprioritized for grid decarbonisation.

Table 9 Summary of avoided emissions – Norway

Avoided Emissions ($MtCO_{2eq}$/yr)	Theoretical 6.75
Total grid emissions in 2022 ($MtCO_{2eq}$/yr)	1.1
Potential Decrease in Electricity Emissions (%)	Complete decarbonisation

As the electricity required to produce hydrogen for export to the EU is greater than the fossil-fuelled electricity in Norway, the maximum avoided emissions are limited to the total emissions from current fossil generation. By not producing hydrogen for export to the EU, grid emissions in Norway would decrease to zero as more electricity is required (15 TWh) to produce hydrogen for export than to replace fossil fuels in the grid (2.38 TWh). Therefore, the grid could be decarbonised and green hydrogen produced with the remaining renewables. The reprioritisation of renewables is contingent on the redirection of investments from hydrogen to renewables, as mentioned. Although there would be emissions avoided in Norway it is likely there will be consequential emissions elsewhere to meet the demand for hydrogen in the EU and elsewhere. These may be higher or lower than the avoided emissions in Norway, depending on several factors.

6.2.4 Environmental, Social and Economic Factors

A feasibility study is being conducted for a pipeline connecting Norway and Germany that will transport both blue and green hydrogen, as well as natural gas, between the two countries[120]. The pipeline is set to eventually transport up to 4 Mt/yr of hydrogen as part of an overall effort to reduce reliance on Russian sourced fuels. Although the move to low carbon hydrogen (green and blue) is a positive step, it is imperative that carbon capture technologies reach high technology readiness, to make blue hydrogen less carbon intensive, and that a long-term lock-in to fossil-based fuels is avoided. Further, environmental impacts in the form of embodied emissions for the infrastructure that will be installed, disrupted ecosystems and strain on services should be considered with respect to the pipeline.

According to the climate action tracker, which considers domestic emissions, Norway's policy and action towards contributing to limiting warming to <1.5°C is almost sufficient[121]. Norway is leading in EV adoption and renewable electricity but still hosts the largest fossil fuel reserves in Europe that are exported around the world[122].

Norway is a leader when comparing the metrics highlighted in previous chapters. The unemployment rate is reported to be 3.4%[123], with very low poverty rates of around 0.5%[124], and the country has a gini coefficient of 27.7[125] (compared to Belgium with a coefficient of 26). This highlights an overall flourishing society, but the opportunities of low carbon hydrogen can support this through creating economic development domestically and internationally.

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[120] https://www.reuters.com/business/energy/europe-takes-steps-toward-developing-hydrogen-pipeline-network-2023-03-02/

[121] https://climateactiontracker.org/countries/norway/

[122] **Based on the climate action tracker, current policies and action are rated as "Almost sufficient", while its NDC target against fair share and net zero targets are rated as still "Insufficient. The exported emissions from Norwegian oil and gas are not considered in the CAT's overall "Almost sufficient" rating. These emissions contribute significantly to global emissions.**

[123] https://tradingeconomics.com/norway/unemployment-rate

[124] https://www.macrotrends.net/countries/NOR/norway/poverty-rate

[125] https://www.theglobaleconomy.com/Norway/gini_inequality_index/

6.3 FURTHER COUNTRY DETAILS

6.3.1 Projects powered by the grid

The majority of the announced projects in Norway will be connected to dedicated renewable sources with only 2 projects planned to be connected to the grid. Since Norway has a large contribution from renewable sources into its grid, connected projects are not expected to pose significant threats to the overall emissions of production.

6.3.2 Water Analysis

Norway has a large number of fjords, lakes, rivers, and a vast coastline stretching along the North Atlantic Ocean. From the total water supply 90% is based on surface water such as lakes and rivers, while 10 % is based on ground water. Of the total water supply 44 % of the water production is going to households and 25 % to industry[126]. Norway is not considered to be at risk from water stress, with an almost 100% potable water access for the Norwegian population. Regarding water for commercial uses, for freshwater and coastal water bodies, there are strong water management systems already in place, and due to the topography, coastline length and geographical location of Norway, there are numerous local water sourcing opportunities[127]. As Norway's political objectives align with enhancing ecological quality, this may conflict with new development that is within or in proximity to certain water bodies[128].

Although over the last century, mainland Norway water system has experienced significant climate shifts. Average temperatures have risen by approximately 0.8°C, which has led to heightened winter and spring stream flow. Early snowmelt now triggers premature spring floods with prolonged low summer stream flow[129]. Additionally, there is lack of sewage water treatment and significant water losses in water supply pipelines leading to overuse of water sources in the industry[130]. It is necessary to optimise water use in the industries by diversifying sources and treating wastewater. With abundant source of water streams and a large coastline stretching for about 2500km with desalination possibility, water availability is not considered as bottleneck for hydrogen production in Norway.

6.3.3 Carbon feedstock requirements

Another e-fuels project in Norway, the Norsk project, plans to utilise recycled biogenic and direct air capture CO_2[131] for production of e-fuels in Norway. In 2020, Norway had the second lowest yearly emissions among the studied countries with 36 Mt CO_2 equivalent[132]. Emissions from transport were the highest CO_2 contributor, followed by electricity and heat production, and the manufacturing industry[133]. For carbon feedstock for recycled carbon fuels, Norway would need to capture industrial point-source emissions. Norway's largest industry is oil and gas, followed by aquaculture, metal, chemicals, and metal. But there may not be many opportunities in future for sourcing CO_2 from industrial emissions, as they would not fall under avoided emission as per European definition after 2040 as explained in 4.3.2.

For biomass-based energy sources, Norway makes use of municipal waste with small contribution from solid biofuels. Although contribution of bio waste in the total energy supply was minimal in 2020[134], there has been a recent increase in biofuel plant developments[135]. It has substantial portions of land that is dominated by mountainous terrain whereby approximately 33% of the area is forest land with presence of timber and woody biomass and 3% is agricultural land[136]. Sawmills use a large volume of (often waste) biomass, mainly for heat. This presents a large potential for biogenic CO_2, but the dispersed nature may be economically challenging

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126 The_water_services_in_Norway_2018.pdf
127 *Voluntary National Review 2021 Norway*
128 *https://www.kartverket.no/kunnskap/Fakta-om-Norge/norges-kystlinje/kystlinjen-i-kilometer (last access: 24 February 2020), 2019*
129 Water and Climate Change Adaptation (oecd.org)
130 Water management and challenges in Norway
131 https://media.uk.norwegian.com/pressreleases/norwegian-partners-with-norsk-e-fuel-to-build-new-e-fuel-plant-in-norway-3247949#:~:text=The%20goal%20is%20to%20start,equity%20stake%20in%20the%20company.
132 https://data.worldbank.org/indicator/EN.ATM.CO2E.KT?locations=NO
133 https://data.worldbank.org/indicator/EN.CO2.TRAN.ZS?locations=NO
134 https://www.iea.org/countries/norway
135 https://www.sum.uio.no/include/publikasjoner-media/sommerstudier/2019/the-role-ryan-hamilton.pdf
136 https://www.ieabioenergy.com/wp-content/uploads/2021/11/CountryReport2021_Norway_final.pdf

Thus, in upcoming projects, Norway has the opportunity to potentially utilise biogenic CO_2, perhaps in combination with direct air capture[137,138].

6.3.4 Cumulative land and water requirements for planned projects that have an EU export focus in Norway

The construction and operation of export scale hydrogen plants with co-located renewables can be considerable. In addition, water requirements for large scale electrolysis are extensive, but largely variable dependent on the water source and electrolyser technology. Ricardo's estimates for the total land and water requirements in Norway, accounting only for projects included in the analysis of this study that have an EU export focus, are below:

Table 10 Total land and water requirements for planned projects that have an EU export focus

Supply Scenario	Km² required	Water Required Mt/y
100% Solar + Electrolysis plant	N.A.	6-9
100% Wind + Electrolysis plant	1427.2 — Equivalent to 132,148 football fields	

6.4 P2X EUROPE & NORDIC ELECTROFUEL – POWER TO LIQUID PLANT

A joint venture between Nordic Electrofuel and P2X Europe to build a power-to-liquid production plant by 2024 for the production of renewable synthetic fuels and waxes will be the focus of a case study to analyse such a plant's requirement, as well as the social and natural value of the proposed site and the project's potential impact.

Figure 9 Planned Power-to-Liquid plant at Heroya, Porsgrunn, Norway (MABANAFT)

137 https://carbonherald.com/norway-considers-introducing-subsidy-for-direct-air-capture-tech/
138 https://www.gasworld.com/story/norway-government-grants-3-5m-for-large-scale-direct-air-capture-pilot/

Hydrogen and renewable plant: The P2X Europe Nordic Electrofuel project aims to initially produce 8 kt of synthetic fuels and waxes[139], ramping up to 800 kt per year by 2032. Initially, production process will consume 1.2 kt of green hydrogen, increasing up to 120 kt. Hydrogen production will use domestic wind and hydro power[140]. The e-fuel facility along with the wind power plant is expected to be located in the Herøya industrial park in Porsgrunn.

Plant Footprint: The Herøya industrial park in Porsgrunn offers industrial plots, approximately 160,000 sq m of multi-functional buildings (Office, workshop, laboratories, warehouse), and a 1.6km quay front [141]. (Full facility rather than any part of it associated with the project). Expected electrolysis plant size for this project will be 8 MWe initially which will be expanded to 800 MWe to match the production increase in 2032[142]. Space requirement for final electrolysis facility size will be 0.18 km^2. The footprint of 2 GW renewable energy plant will be 688 km^2 assuming that half the electricity is supplied from wind power[143] and remaining from an operational hydropower plant (no further land for construction and installation is required).

Social & natural value: Herøya industrial park is a leading innovation and development hub for industrialisation and commercialisation of technological and industrial ideas. It hosts a number of cross functional companies and comprises numerous industrial facilities. It is present on the coast of Oslo fjord, which gives easy access to shipping.

Analysis: Herøya industrial park boasts a notable hydrogen supporting infrastructure with the world's first fully automated electrolyser production facility[144] and a hydrogen plant of 24 MW is already being installed in this location through the repurposing of an old compressor hall in 2023. This refurbishment is the largest hydrogen factory of its kind built inside a building[145] and represents an interesting pilot project when considering the relatively lower environmental impact when compared to greenfield projects for similar infrastructure.

7. STUDY COUNTRY: CHILE

7.1 INTRODUCTION

Chile is set to be a major producer within the global hydrogen market, with ambition to reach 25 GW capacity by 2030. Chile boasts some of the most abundant renewable resources in the world and is one of high income countries with plans to become a major exporter. There are currently around 58,000 tonnes of hydrogen produced in Chile that is predominantly carried out by industrial gas producers and used as chemical feedstock, with no operational green hydrogen plants to date[146].

To date, Chile lacks hydrogen specific regulation and there is no specific regulatory body responsible for hydrogen regulation. Following the release of the countries hydrogen strategy, the Chilean government set out a regulatory roadmap that contemplates a series of regulations that includes: (i) the Hydrogen Facilities General Regulation; (ii) the Multi-Fuel Service Stations Regulation; (iii) the Technical, Construction and Security Requirements for GH2 (gaseous state hydrogen) Powered Vehicles Regulation; and (iv) the Hydrogen Systems for Mining Operations Regulation, among others[147].

[139] https://www.mabanaft.com/en/news-info/current-news-and-press-releases/news-detail/products-for-the-future-p2x-europe-and-nordic-electrofuel-cooperate-on-ptl-products/

[140] https://www.mynewsdesk.com/uk/mabanaft/pressreleases/products-for-the-future-p2x-europe-and-nordic-electrofuel-cooperate-on-ptl-products-3154054

[141] Setting up at Herøya (heroya-industripark.no)

[142] Assuming there is 15% hydrogen content in the e-fuels and electrolyser efficiency is 50MWh/ton

[143] Footprint for wind energy plant is 85 acres/MW

[144] Nel ASA: Official opening of the Herøya facility | Nel Hydrogen

[145] https://www.heroya-industripark.no/en/news/the-worlds-largest-and-first-green-hydrogen-plant-starts-production-at-heroeya-in-2023

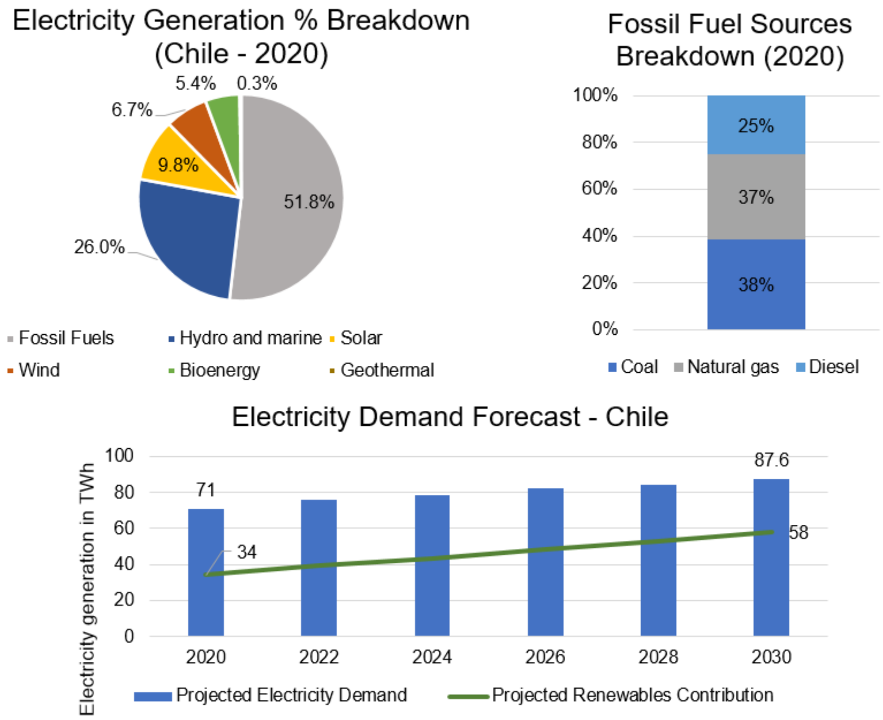
[146] Hydrogen law and regulation in Chile | CMS Expert Guides

[147] Chile: Green Hydrogen - Background, regulation and future - Baker McKenzie InsightPlus

7.2 BACKGROUND & COUNTERFACTUAL

7.2.1 Electricity grid context

Figure 10 Electricity generation mix in Chile (2020) and electricity demand forecast



Chile's population is provided with 100% electricity access, as per the World bank, 51.8% of this electricity coming from fossil fuel sources and the remaining 48.2% sourced from renewables – which have been linearly increasing from 2018 (Figure 10). Given the still significant reliance on fossil fuels, the carbon intensity of Chile's grid is currently at 333 gCO_2/kWh[148]. The electricity demand in 2030 is forecasted to increase to 87.6 TWh, assuming no H_2 production, with renewables supplying 66% of the electricity mix. Any additional demand from electrolysers could drive more fossil fuels onto the grid, as these are generally the marginal power plants. It is also useful to note that Chile has insignificant fossil fuel resources of its own and as a result is highly reliant on imports and vulnerable to global price volatility. This highlights the need for the current fossil dependency to be replaced with more renewable forms of energy such as solar, wind, hydro and bioenergy to reduce the carbon intensity of the grid and increase resilience. This exposes a competing demand for renewable electricity to green H_2 production.

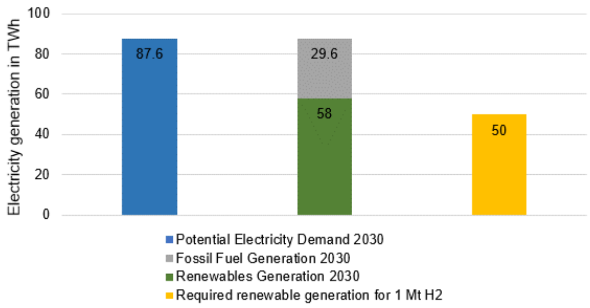
7.2.2 Hydrogen Strategy and Planned Projects

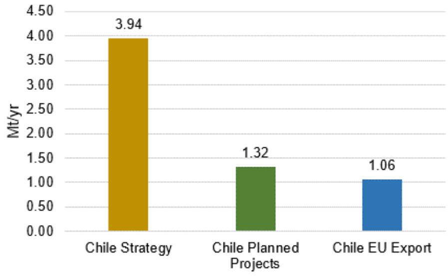
To produce 1 Mt of H_2, around the expected amount to be exported to the EU, renewable generation of around 50 TWh would be required. This is equivalent to 70% of Chile's delivered generation in 2020. This, including the already forecasted renewable capacity of 58 TWh in 2030 means all electricity demand could be met by renewables if H_2 production were not prioritised. This numerically highlights the climate benefit of prioritising renewables for grid decarbonisation in Chile. Chile's H_2 strategy aims to supply 3.94 Mt/yr of H_2 by 2030 with domestic consumption assumed to constitute around three quarters of supply and the rest to be exported to the likes of the EU[149] by 2030 (Figure 11).

[148] https://ourworldindata.org/grapher/carbon-intensity-electricity?tab=table

[149] https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf

Figure 11 Comparison of required renewable generation and projected electricity demand (2030) alongside comparison of 2030 targets in H_2 strategy, planned projects and expected EU exports





7.2.3 Avoided and Consequential Emissions

The table below summarises the potentially avoided emissions if renewables originally intended for green hydrogen to be exported to the EU (50 TWh) were reprioritized for grid decarbonisation.

Table 11 Summary of avoided – Chile

Avoided Emissions ($MtCO_{2eq}$/yr)	Theoretical 35.9
Total grid emissions in 2022 ($MtCO_{2eq}$/yr)	26.4
Potential Decrease in Electricity Emissions (%)	Complete decarbonisation

As the electricity required to produce hydrogen for export to the EU is greater than the fossil-fuelled electricity in Chile, the maximum avoided emissions are limited to the total emissions from current fossil generation. By not producing hydrogen, grid emissions in Chile would decrease to zero as more electricity is required (50 TWh) to produce hydrogen for export than to replace fossil fuels in the grid (37 TWh). This highlights that the grid could be decarbonised and green hydrogen produced with the remaining renewables. The reprioritisation of renewables is contingent on the redirection of investments from hydrogen to renewables, as mentioned. Although there would be emissions avoided in Chile it is likely there will be consequential emissions elsewhere to meet the demand for hydrogen in the EU and elsewhere. These may be higher or lower than the avoided emissions in Chile, depending on several factors.

7.2.4 Environmental, Social and Economic Factors

There will be emissions related to the transportation of the hydrogen if it were to be exported to the EU from Chile. Santiago to Rotterdam by cargo is approximately 15,000 km and for 1 Mt/yr of hydrogen exported, the shipping of the H_2 could amount to around 300,000 tCO_{2eq}/year, more than 64,000 typical passenger cars in one year[150]. These emissions will be unabated until the shipping industry manages to decarbonise operations, which will likely be after 2030. Further emissions would be related to the transport that may be required to the demand point within the EU.

According to the climate action tracker, Chile's progress in meeting their nationally determined contributions according to the Paris Agreement through action and policy is insufficient[151]. This means that the reduction of carbon across sectors has not been rapid enough to remain within a <2°C warming target. This highlights that the country needs to find alternative sources of energy to decarbonise domestic activities, including renewables and potentially green H_2 or one of its derivatives.

[150] https://www.epa.gov/greenvehicles/tailpipe-greenhouse-gas-emissions-typical-passenger-vehicle
[151] https://climateactiontracker.org/countries/chile/

Chile, although a country progressing socio-economically in the region, still has high income disparity with a gini coefficient of 44.9 and unemployment levels at around 8%[152,153]. Poverty has been reported to be 11.5%[154]. As part of Chile's green H_2 strategy, the pillars of action include using the fuel as an efficient pathway to net-zero for the country and a catalyst for further local growth. Moreover, the action plan prioritises social and local development as well as capacity sharing and innovation. These elements are crucial in addressing issues like unemployment, inequality and local economic development whilst driving national decarbonisation.

7.3 FURTHER COUNTRY DETAILS

7.3.1 Projects powered by grid

It was found that very few plan to extract power from the grid, with one utilising renewable energy supplied from the grid and another using a combination of wind, solar, and grid power. As a result, emissions linked to the production of hydrogen/e-fuel projects in Chile are expected to be low and have minimal impact on grid stability.

7.3.2 Water analysis

The water systems in Chile can be categorized into three distinct regions. In the south, there is abundant rainfall and large rivers. In the middle, it is less rainy but still a moderate level of moisture. Then, in the northern area, including the Atacama desert, there are extremely dry areas, and very little rainfall[155]. In Chile water demand mainly comes from agriculture taking up 72% of the total consumption, followed by use of water for drinking (12%), industries (7%), and mining (4%)[156]. The rest is used for making electricity and raising livestock. They also have one of the highest irrigation water application rates among the Organisation for Economic Co-Operation and Development (OECD) countries and Illegal water extraction takes place in areas facing water scarcity[157].

According to Chile's long term climate strategy document, over the past 30 years, country has seen decrease in water availability of 20% in the southern areas and a 50% drop in the north-central regions. The problem is linked to rising temperatures, which cause ice to melt faster and reduce water in glaciers. The rainfall patterns have also changed, making the situation worse[158]. Chile has also been experiencing a mega-drought, placing the country at high risk from water stress[159]. Climate change impacts, in combination with intensive agriculture irrigation and the existing water management system are attributed to this water scarcity[160]. With current predictions of global warming rates, Chile's state of water scarcity is expected to climb further[161].

This presents a challenge in sourcing local freshwater toward the production of hydrogen without compounding the existing water stress. However, Chile has 6437 km of coastline thereby presenting the opportunity for seawater electrolysis thus reducing or removing the need for freshwater input. Chile has the largest desalination system operating in South America and the government has proposed policy measure to promotes the use of desalinated water in agriculture and mining sectors[162].

7.3.3 Carbon feedstock requirements

Synthetic hydrocarbons projects in Chile plan to use direct air carbon capture technology to source the carbon required in the production process. One e-methanol plant in Antofagasta plans to use captured carbon dioxide,

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[152] https://www.statista.com/statistics/983056/income-distribution-gini-coefficient-chile/#:~:text=Between%202010%20and%202021%2C%20Chile's,the%20Gini%20coefficient%20reached%2044.9.
[153] https://tradingeconomics.com/chile/unemployment-rate
[154] https://www.worldbank.org/en/country/chile/overview
[155] Chile geography, maps, climate, environment and terrain from Chile | - CountryReports
[156] Modernization of Chile's Water Code
[157] Water-Resources-Allocation-Chile.pdf (oecd.org)
[158] CHL_LTS_2021_EN_revised-avs.docx (unfccc.int)
[159] *Water | Free Full-Text | Water Crisis in Petorca Basin, Chile: The Combined Effects of a Mega-Drought and Water Management (mdpi.com)*
[160] *Climate change projections of temperature and precipitation in Chile based on statistical downscaling | SpringerLink*
[161] *Ranking the World's Most Water-Stressed Countries in 2040 | World Resources Institute (wri.org)*
[162] Current situation and major challenges of desalination in Chile

though it is unclear if it will be capturing from direct air or industrial emissions[163]. Another plant, Haru Oni in Magallanes region, will produce e-gasoline and e-liquefied gas using direct air capture[164].

Chile produced over 84 Mt of CO_2 equivalent[165] emissions in 2020, largely as a result of electricity and heat production followed by the transport and manufacturing industry. The country could use the CO_2 generated from the combustion of fossil fuels in heat and electricity production as carbon feedstock for e-fuels. In this case, until 2040 Chile could source the CO_2 from the manufacturing industries such as cement, iron, and steel by paying a carbon price for the emissions.

A more sustainable carbon source could be biogenic carbon. Although agriculture is one of the main economic activities in Chile, there is low usage of biomass for electricity production. Biofuels contributed to just 6.5% of the total electricity generation in 2021, though 16% of the total energy supply was based on biofuels and waste[166]. It is likely that the uses are dispersed geographically, potentially making collection, storage, and transportation for use as a carbon source unattractive. Currently, none of the e-fuel projects in Chile are planning to use carbon extracted from biomass.

7.3.4 Cumulative land and water requirements for planned projects that have an EU export focus in Chile

The construction and operation of export scale hydrogen plants with co-located renewables can be considerable. In addition, water requirements for large scale electrolysis are extensive, but largely variable dependent on the water source and electrolyser technology. Ricardo's estimates for the total land and water requirements in Chile, accounting only for projects included in the analysis of this study that have an EU export focus, are below:

Table 12 Total land and water requirements for planned projects that have an EU export focus

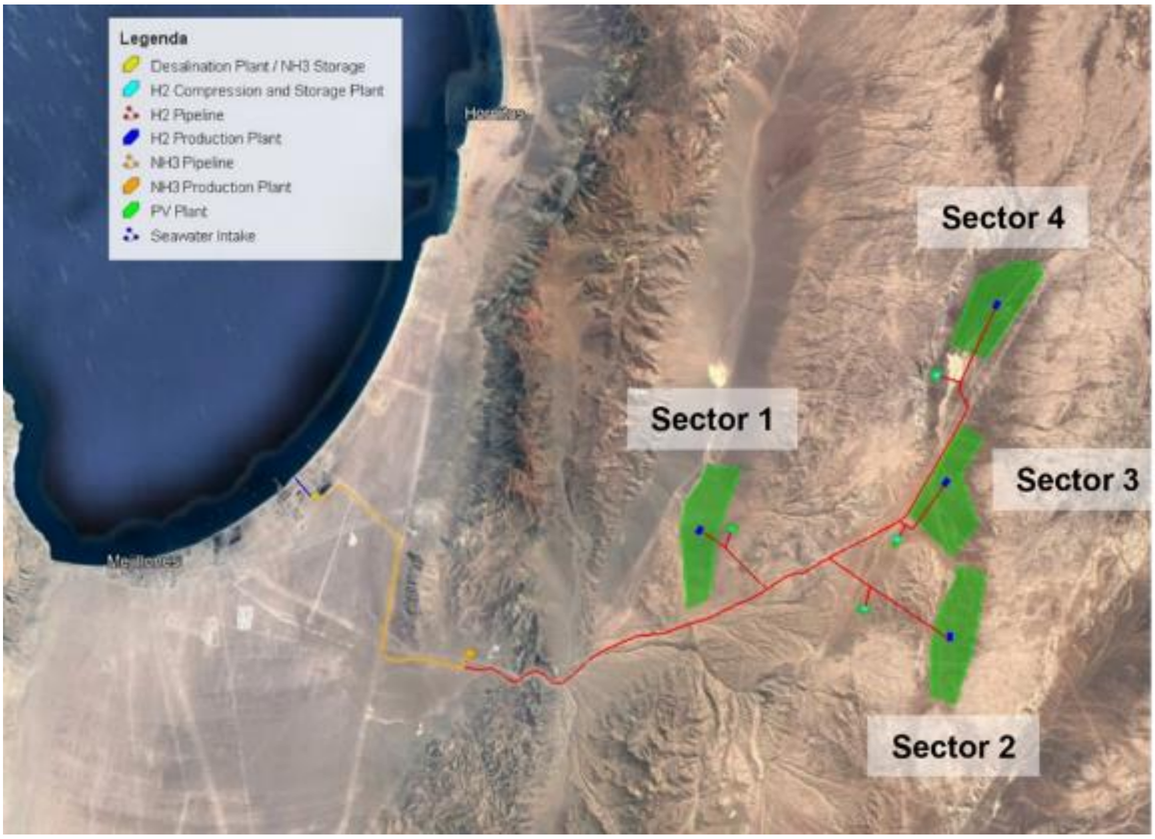
Supply Scenario	Km² required		Water Required Mt/y
100% Solar + Electrolysis plant	614.60	Equivalent to 56,907 football fields	21.23-31.84
100% Wind + Electrolysis plant	6089.14	Equivalent to 563,809 football fields	

7.4 ATACAMA HYDROGEN HUB

Atacama Hydrogen Hub is the largest export orientated project in Chile and has therefore been chosen as a case study. This case study will analyse the physical space and water requirements for such a project as well as the social and natural value of the surrounding area. This case study considers the entire project across both phases of roll out.

[163] https://renewablesnow.com/news/six-green-h2-projects-in-chile-to-split-usd-50m-in-state-funds-767487/
[164] https://hifglobal.com/location/haru-oni/
[165] https://data.worldbank.org/indicator/EN.ATM.CO2E.KT?locations=CL
[166] https://www.iea.org/countries/chile

Figure 12 Atacama hydrogen hub map



The plant: Atacama Hydrogen Hub project is the largest export-oriented project proposed in Chile. This 2 GW electrolysis facility will be powered with off-grid solar PV and it plans to include a desalination plant to support the water requirement in the production process. The region is known to be the best solar location of the world with mild temperatures throughout the year. Hydrogen will be transported using hydrogen powered freight train for the mining sector[167] and a gas pipeline to Mejillones bay[168] for final connection to load port.

Plant land use and water requirement: The footprint of this hydrogen plant[169] including supporting equipment will require approximately 0.272km^2 of land. Assuming there is a 4 GW solar plant[170] to fulfil the energy requirements for electrolysis, this would require 492km^2 of land[171]. It is estimated that a plant of this size would require between 2.2-3.3 million tonnes of water.

Social & natural value:

The Atacama Desert is a geographically significant area. Its inner core is believed to have been hyper arid for around 15 million years as a result of its unique conditions and therefore makes it one of the oldest deserts in the world. The desert's unique conditions have made it a centrepiece for astronomical research for decades. The elevation and clarity of the desert is the reason that networks of telescopes have been placed there, including the European Space Observatory telescope that helped identify the TRAPPIST-1 system of planets. In addition, the desert has the highest UV radiation levels and some of the lowest rainfall on Earth, which is why it has been used as a Mars analogue model for 20 years[172].

[167] https://www.canninghouse.org/storage/uploads/events/2021-events/06-june/2506-juan-carlos-jobet/Slides_Chiles_Green_Hydrogen_Strategy_lbzgf.pdf

[168] Atacama Hydrogen Hub

[169] Assuming space requirement for hydrogen production facility along with balance of plant is 136m^2/MW electrolysis capacity- Hydrogen supply chain evidence base (publishing.service.gov.uk)

[170] This assumption is based on the sizing ratio of the nearby San Pedro De Atacama project. Size ratios can vary significantly dependent on business model

[171] Assuming land requirement is 123acres/MW

[172] https://doi.org/10.3389/fspas.2021.810426

In addition to its natural and scientific value, the Atacama Desert has become a popular tourist destination. The desert itself is said to be one of the top three destinations to visit in Chile, with San Pedro de Atacama receiving hundreds of thousands of visitors per year.

Analysis: The area for the hydrogen hub shown on its official website was analysed (Figure 12) and only desert area was seen in the allocated region. Moreover, Atacama Desert has a solar power plant present since 2015[173]. Given the region is experienced with solar plant implementation, it is not expected to be difficult to replicate on a larger scale. Given the size of the accompanying solar plant for electrolysis at this site, there is a risk that the land itself could be negatively impacted. The area's scientific significance could also increase the severity of regularly encountered risks from a natural and social value standpoint. In the short term, the construction of the hydrogen plant itself along with creation of connecting roads and associated infrastructure will cause various noise and debris pollution that could affect local species, habitats, and air quality. These impacts are explored in more detail in Section 3.

In addition, one of the greatest risks to this particular area could be the water disposal from the electrolytic process. Many regions of the Atacama Desert see just one millimetre of rainfall per year, meaning its flora and fauna has greatly adapted to survive in such conditions. An overage of water from anthropogenic activities in any part of the desert could have a detrimental impact on local ecosystems.

8. STUDY COUNTRY: NAMIBIA

8.1 INTRODUCTION

Namibia is actively pursuing energy self-reliance and sustainability, aiming to reduce its reliance on neighbouring countries for electricity. While currently importing 50-70% of its power from Zambia, Zimbabwe, and South Africa, Namibia has embraced renewable energy with 160 MW of operational capacity, supplemented by an additional 214 MW in the pipeline through independent power producers (IPPs)[174]. Additionally, Namibia has set its sights on a greener future by adopting a green hydrogen strategy. The strategy aspires to produce 10-12 million tonnes of hydrogen equivalent annually by 2050[175]. A crucial catalyst in this is the $10 billion Hyphen Hydrogen Energy project[176], representing a step in implementing the Namibian government's determined push to establish a large-scale green hydrogen industry.

Currently, there are no policies, regulations, or law surrounding green hydrogen in Namibia[177].

[173] https://www.sonnedix.com/atacamasolar

[174] https://energynews.biz/namibia-emphasizes-its-goals-and-objectives-for-green-hydrogen/

[175] https://gh2.org/countries/namibia

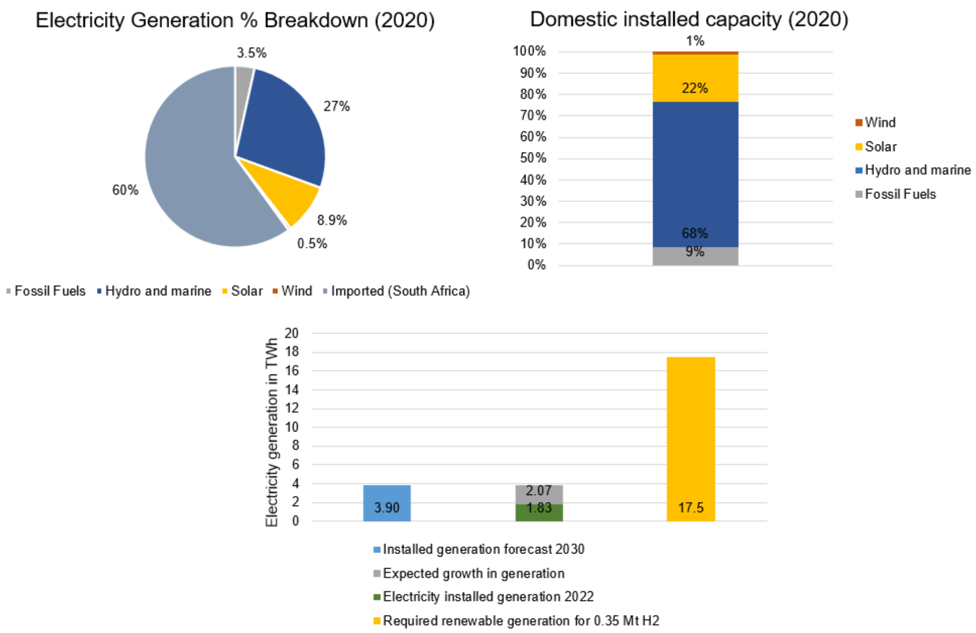
[176] https://www.esi-africa.com/industry-sectors/future-energy/namibia-roadshow-to-provide-insight-into-green-hydrogen-project/

[177] https://www.namibian.com.na/lack-of-green-hydrogen-regulation-a-setback/#:~:text=IT%20IS%20NO%20secret%20that%20Namibia%20currently%20has,be%20no%20laws%20governing%20its%20production%20and%20use.

8.2 BACKGROUND & COUNTERFACTUAL

8.2.1 Electricity grid context

Figure 13 Electricity generation mix in Namibia (2020) and comparison of required renewable generation and projected electricity demand (2030)[178][179]



As of 2020, the domestic generation capacity of Namibia is made up of mainly hydro-electric (68%) followed by solar (22%), fossil fuels (9%) and wind (1%). Although this mix is predominantly renewables, Namibia imported 60% of its electricity mainly from South Africa which has a grid supplied by mainly coal fired generation. When only considering domestic generation, the grid intensity of Namibia's grid is 64 gCO_2/kWh[180] but the true intensity would be higher given the large imports of fossil derived electricity (South Africa has a grid emissions intensity of 709 gCO_2/kWh for comparison). Not only is Namibia highly reliant on electricity imports but less than 50% of the population has access to electricity[181].

Peak demand is projected to rise to 3.9 TWh by 2030, based on work by DLA Piper, without considering imports. It is assumed that imports would likely increase in a similar fashion. To get a sense of scale, the figure above compares the electricity required to produce 0.35 Mt/yr of hydrogen, the expected EU export quantity, with the electricity system in 2020 and 2030. This shows that the total domestic installed generation as of 2020 would need to increase by about 10 times to produce 0.35 Mt/yr of hydrogen and draws attention to the significant development which would be needed to achieve this target. The significant reliance on electricity imports and low access of electricity are challenges which put into question the prioritisation of green hydrogen development without addressing these issues.

[178] https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Africa/Namibia_Africa_RE_SP.pdf

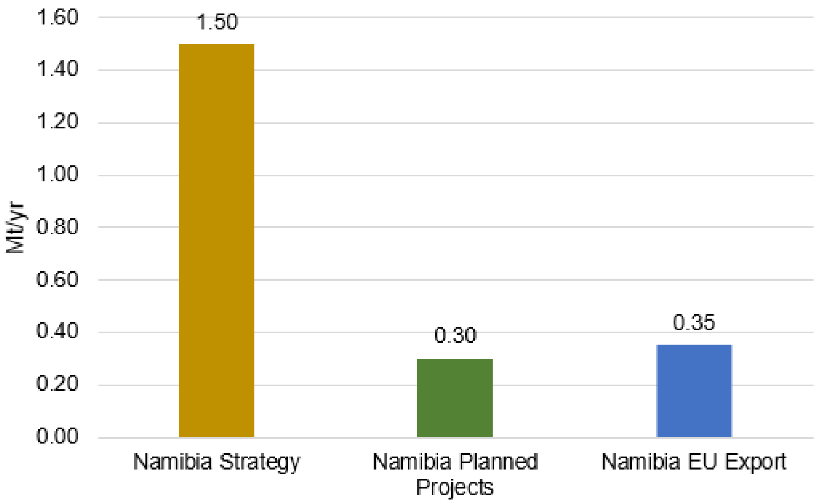
[179]https://www.usaid.gov/powerafrica/namibia#:~:text=While%20the%20country's%20generation%20mix,Africa%20Power%20Pool%20(SAPP).

[180] https://ourworldindata.org/grapher/carbon-intensity-electricity?tab=table

[181] https://www.dlapiper.com/en-GB/insights/publications/2022/11/africa-energy-futures/africa-energy-futures-namibia

8.2.2 Hydrogen Strategy and Planned Projects

Figure 14 Comparison of 2030 targets in H_2 strategy, planned projects and expected EU exports[182][183]



The Namibian government has the aim of reaching production volumes of 1-2 Mt/yr by 2030 and is aiming to reach 10-15 Mt/yr by 2050. Based on the Hyphen project the EU will be an importer of up to 0.35 Mt/yr of hydrogen from Namibia by 2030. Currently the planned projects in the country amount to a similar amount, 0.3 Mt/yr, showing there is much to be done to achieve the ambitious target of 1-2 Mt/yr production by 2030 set by the government.

8.2.3 Avoided and Consequential Emissions

The table below summarises the potentially avoided emissions if renewables originally intended for green hydrogen to be exported to the EU (17.5 TWh) were reprioritized for grid decarbonisation. As Namibia imports much of its fossil-fuel electricity from South Africa (with smaller quantities from Zambia and Zimbabwe), the avoided emissions are based on these imports and Namibian generation.

Table 13 Summary of avoided emissions – Namibia

Avoided Emissions ($MtCO_{2eq}$/yr)	Theoretical 15.6
Total grid emissions in 2022 ($MtCO_{2eq}$/yr)	2.59
Potential Decrease in Electricity Emissions (%)	Complete decarbonisation

By not producing hydrogen, grid emissions in Namibia would decrease to zero as more electricity is required (17.5 TWh) to produce hydrogen for export than to replace mainly imported fossil fuel electricity in the grid (2.9 TWh). Therefore, the grid could be decarbonised, further expanded to increase access to electricity and green hydrogen produced with the remaining renewables. The reprioritisation of renewables is contingent on the redirection of investments from hydrogen to renewables, as mentioned. Although there would be emissions avoided in Namibia (and its electricity-supplying neighbours) it is likely there will be consequential emissions elsewhere to meet the demand for hydrogen in the EU and elsewhere. These may be higher or lower than the avoided emissions due to Namibia, depending on several factors.

8.2.4 Environmental, Social and Economic Factors

Walvis Bay to Rotterdam by cargo is approximately 12,000 km and for every 0.35 Mt/yr of hydrogen exported, the shipping of the H_2 could amount to around 229,000 tCO_{2eq}/year, more than 49,700 typical passenger cars in one year[184]. These emissions will be unabated until the shipping industry manages to decarbonise

[182] https://gh2namibia.com/gh2_file_uploads/2022/11/Namibia-GH2-Strategy-Rev2.pdf
[183] https://www.euractiv.com/section/energy-environment/news/namibia-moves-ahead-on-green-hydrogen-project-with-german-investors/
[184] https://www.epa.gov/greenvehicles/tailpipe-greenhouse-gas-emissions-typical-passenger-vehicle

operations, which will likely be after 2030. Further unabated emissions would be related to the transport that may be required to the demand point within the EU.

The Paris Agreement came into effect in Namibia only in 2016, meaning there is no meaningful data tracking the progress of the country based on nationally determined contributions (NDCs). Although this is the case, the country's heavy reliance on electricity imports, which are significantly carbon intense, means that some progress is clearly required to ensure secure and clean electricity and energy.

Socio-economically, Namibia is very unequal and is comparable to its neighbour South Africa (63)[185], with a gini coefficient of 59.1[186]. Namibia is amongst one of the most economically unequal countries. Unemployment levels have been reported at around 21%[187] and multidimensional poverty at 43%[188]. The development of green hydrogen, under the right governance framework, presents an opportunity to improve aspects such as joblessness and inequality in Namibia, alongside helping to meeting environmental ambitions.

8.3 FURTHER COUNTRY DETAILS

8.3.1 Projects powered by the grid

From data collected and analysed as part of this study, there are no announced projects in Namibia at feasibility stage or advanced that plan to use grid power. New solar and wind energy plant installation will take place for the hydrogen projects in Namibia.

8.3.2 Water Analysis

Namibia is one of the biggest and driest countries in sub-Saharan Africa. It is characterized by high climatic variability in the form of persistent droughts, unpredictable and variable rainfall patterns, variability in temperatures and scarcity of water. The mean annual rainfall ranges from just above 600 mm in the Northeast to less than 25 mm in the Southwest and West of the country[189]. Around 45% of Namibia's water comes from groundwater sources, 33% from the Border Rivers, mainly in the north, and about 22% from impoundments on ephemeral river[189].

Namibia has a high risk of water stress due to its arid location, where high solar radiation, low humidity and high temperature create high evaporation rates[190]. This water scarcity is exacerbated by climate change, competition with neighbouring countries for water availability and urbanised population expansion[191]. Key economic sectors of Namibia are agriculture, livestock, fishing, mining, and manufacturing, with agriculture comprising up to 75% of the total water use in the country. However, water productivity in the agriculture sector is very poor. Additionally, Only 12% of all the water available is used by people at home, and cities use three times more water than the countryside areas[192].

Namibia is deeply impacted by climate change, especially concerning water resources. Shifts in rainfall patterns from neighbouring countries are causing significant reductions in river water. By 2050, a 10-20% drop in rainfall could lead to a 20-30% decrease in northern Namibia's rivers[189]. High temperatures worsen the situation by increasing evaporation and drying crucial wetlands. Groundwater sources are also under threat, with wells at risk of drying up due to insufficient recharge. Coastal areas face challenges from rising sea levels, risking freshwater sources. These changes not only threaten drinking water but also jeopardize agriculture, potentially reducing food production[190]. The water situation is not promising but with 1500 km of coastline, there is opportunity for desalination. Historically, Namibia has not relied on desalination plants but recently government has recently stepped up the construction of second desalination project in the country[193].

[185] https://www.theglobaleconomy.com/South-Africa/gini_inequality_index/
[186] https://www.theglobaleconomy.com/Namibia/gini_inequality_index/
[187] https://tradingeconomics.com/namibia/unemployment-rate
[188] https://ophi.org.uk/namibia-mpi-report-2021/
[189] Microsoft Word - Namibia - NC4 - Final.docx (unfccc.int)
[190] *15931-WB_Namibia Country Profile-WEB.pdf (worldbank.org)*
[191] *A review on water security and management under climate change conditions, Windhoek, Namibia - ScienceDirect*
[192] landscapesnamibia.org/mudumu/sites/default/files/resources/Namibia Climate Change Vulnerability and Adaptation Assessment.pdf
[193] Government to expadiate project for Second Desalination Plant in Namibia (constructionreviewonline.com)

8.3.3 Carbon feedstock requirements

Namibia has no planned e-fuel projects and has the lowest CO_2 emissions compared to other countries included in this study[194]. Namibia's industrial sector is underdeveloped, and the majority of economic activity is seen in fishing and agriculture as well as mining. This suggests that there may not be a significant industrial source of CO_2.

Biowaste contributes to 22% in the total energy mix[195] and although Namibia has minimal small forest cover[196], it does pose significant potential for biomass generation in the form of encroacher bushes, crop residue, and municipal solid waste. Namibia could therefore consider using biogenic CO_2 for production of e-fuels along with direct air capture.

8.3.4 Cumulative land and water requirements for planned projects that have an EU export focus in Namibia

The construction and operation of export scale hydrogen plants with co-located renewables can be considerable. In addition, water requirements for large scale electrolysis are extensive, but largely variable dependent on the water source and electrolyser technology. Ricardo's estimates for the total land and water requirements in Namibia, accounting only for projects included in the analysis of this study that have an EU export focus, are below:

Table 14 Total land and water requirements for planned projects that have an EU export focus

Supply Scenario	Km² required		Water Required Mt/y
100% Solar + Electrolysis plant	258.07	Equivalent to 23,895 football fields	7-10.5
100% Wind + Electrolysis plant	1176.05	Equivalent to 164,449 football fields	

8.4 HYPHEN GREEN HYDROGEN – TSAU KHAEB NATIONAL PARK

Land Use: Hyphen Green Hydrogen Project will be developed on 4000 km² of land within the Tsau Khaeb National Park in Namibia.

Hydrogen and renewable plant: The project will involve construction of ~7 GW of solar and wind renewable energy plants as well as ~3 GW of electrolyser infrastructure for hydrogen production with aims to achieve 350,000 tonnes of green hydrogen production each year[197], which will then be converted to green ammonia[198], before being exported to Europe[199].

Social & natural value: This place is a protected area and is the most biodiverse region in Namibia with a remarkable wealth of flora and fauna, due to limited human intervention in the area for 100 years[200]. The succulent Karoo is an ecoregion stretching along the coastal strip of southwestern Namibia and is a centre of diversity and endemism for reptile and many invertebrates[201], boasts numerous mountains, and has been

194 https://data.worldbank.org/indicator/EN.ATM.CO2E.KT?locations=NA
195 https://www.iea.org/countries/namibia
196 Forest data: Namibia Deforestation Rates and Related Forestry Figures (mongabay.com)
197 Projects - Hyphen Hydrogen Energy (hyphenafrica.com)
198 Namibia launches 10 billion dollar-hydrogen project with German participation | Clean Energy Wire
199 Hyphen and Namibia agree next phase of $10 billion green hydrogen project | Reuters
200 Tsau ǁKhaeb Sperrgebiet National Park - Wikipedia
201 Succulent Karoo - Wikipedia

declared as the only arid biodiversity hotspot in the world[202], with numerous endemic plant and animal species. It is a popular wildlife destination due to presence of Hyena, springbok and marine wildlife including Heaviside's dolphin and southern right whale. It is a significant historical site since it was a proclaimed diamond area. Currently there are no renewable energy plant installation in this region.

Analysis:

The area proposed for the project has significant biodiversity including hundreds of plant and animal species. As some of the plants are endemic to the area, they are already highly susceptible to extinction due to, among other things, climate change. With the development of any infrastructure involving clearing of land to construct renewable energy systems, electrolyser facilities, and transport links, the potential to expedite the extinction of already threatened plant and animal species is significant.

9. STUDY COUNTRY: MOROCCO

9.1 INTRODUCTION

Morocco aims to take a leading role in Africa's green hydrogen production due to its abundant solar and wind resources. The nation's potential, estimated at around 528 GW of renewable energy capacity, makes it an attractive location for producing green hydrogen. Morocco has committed to achieve 52% renewable energy by 2030. The country's Green Hydrogen Production Plan, initiated in 2020, aims to establish 4 GW of green hydrogen capacity by 2030, and its strategic geographic proximity to Europe further enhances its export potential. Additionally, ongoing hydrogen projects are establishing partnerships with considerable international players[203].

Established through the National Hydrogen Commission in 2019, Morocco has a strategy outlined in a 2021 roadmap. The vision includes increasing hydrogen demand to 30 TWh by 2030 and 307 TWh by 2050, necessitating 2 GW of renewable energy capacity. Leveraging its renewable energy model and strategic location, Morocco's green hydrogen potential is aimed to be optimised through short-term pilot projects (2020-2030), medium-term cost-effective production (2030-2040), and long-term sector expansion (2040-2050)[204]. The roadmap also emphasises domestic ammonia production to reduce imports.

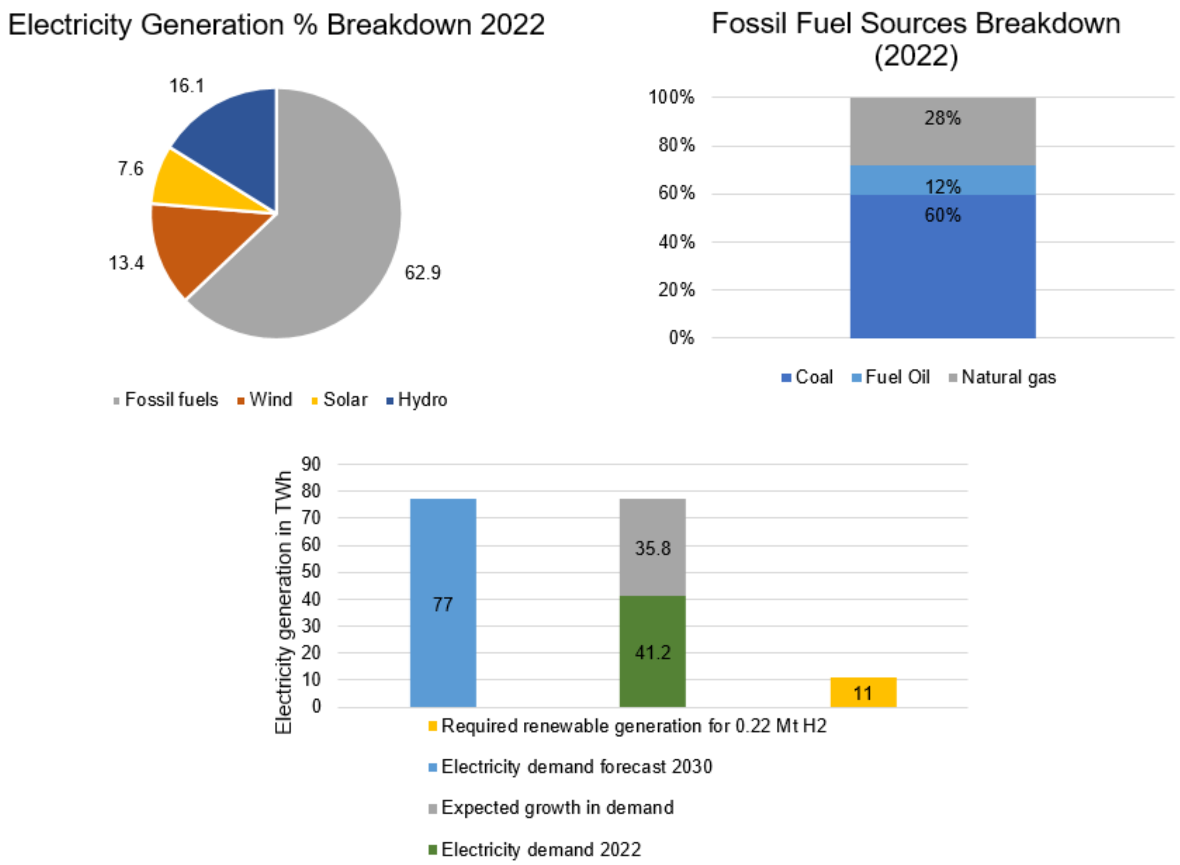
9.2 BACKGROUND & COUNTERFACTUAL

9.2.1 Electricity Grid Context

The 41.2 TWh supplied in 2022 by the Moroccan electricity system was made up of approximately 63% fossil fuels, 13% wind, 8% solar and 16% hydro. With regards to the fossil fuel contribution, the dominant fuel utilised is coal (60%) followed by natural gas (28%) and fuel oil (12%).

[202] Namibia: Plants in Sperrgebiet Area At Risk - allAfrica.com
[203] https://www.energycircle.org/2023/04/10/moroccos-promising-green-hydrogen-sector/
[204] Morocco | Green Hydrogen Organisation (gh2.org)

Figure 15 Electricity generation mix in Morocco (2022) and comparison of required renewable generation and projected electricity demand (2030)[205][206][207]



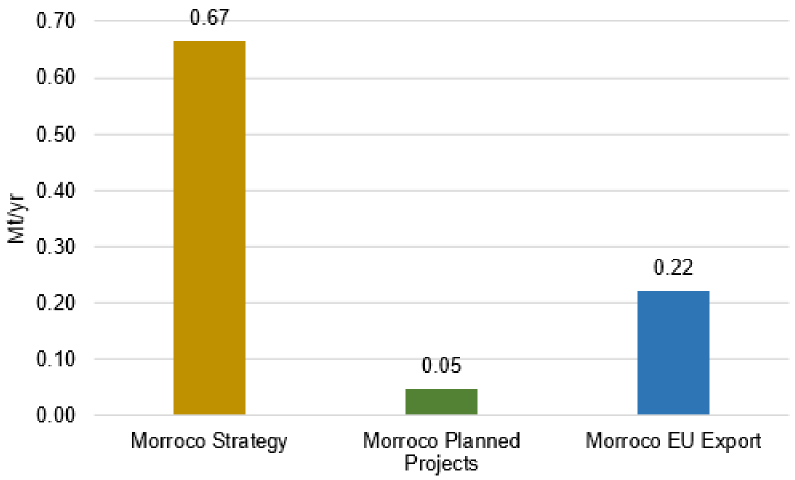
Morocco's grid has a high emissions intensity of 610 gCO_2/kWh given the significant consumption of coal and gas[208]. From 2017 the entire Moroccan population had access to electricity, though with high emissions intensity.

By 2030 the peak demand is expected to reach 77 TWh which would require a further 35.8 TWh supply compared to 2022, as seen above. The figure further highlights the size of renewables development required to meet 0.22 Mt/yr production of hydrogen, the anticipated EU export amount, as compared to the existing and future electricity systems. The fact that the renewables capacity required to produce 0.22 Mt/yr is 27% of the electricity supply as per 2022 shows the extent to which the system will need to be developed. Additionally, there is a clear tension between the prioritisation of renewables capacity for hydrogen production as opposed to grid decarbonisation as 11 TWh of fossil fuels could be displaced.

[205] https://www.trade.gov/country-commercial-guides/morocco-energy
[206] https://www.statista.com/statistics/1238342/electricity-production-in-morocco/
[207] Potential peak electricity demand 55-77 TWh https://www.nrel.gov/docs/fy21osti/77427.pdf
[208] https://ourworldindata.org/grapher/carbon-intensity-electricity?tab=table

9.2.2 Hydrogen Strategy and Planned Projects

Figure 16 Comparison of 2030 targets in H2 strategy, planned projects and expected EU exports



Morocco has set out an ambitious strategy to produce 0.67 Mt/yr of hydrogen a year by 2030, with 0.22 Mt/yr to be exported to the EU. The current announced projects, however, only amount to 0.05 Mt/yr showing a significant deficit between announcements and progress. To produce the amounts of hydrogen stated in the strategy will require significant renewables generation which has land, water, and infrastructure implications.

9.2.3 Avoided and Consequential Emissions

The table below summarises the potentially avoided emissions if renewables originally intended for green hydrogen to be exported to the EU (11 TWh) were reprioritized for grid decarbonisation.

Table 15 Summary of avoided emissions – Morocco

Avoided Emissions ($MtCO_{2eq}/yr$)	8.45
Total grid emissions in 2022 ($MtCO_{2eq}/yr$)	20.4
Potential Decrease in Electricity Emissions (%)	42

By not producing hydrogen, grid emissions in Morocco would decrease by ~42% which could be significant with regards to decarbonising the grid. The reprioritisation of renewables is contingent on the redirection of investments from hydrogen to renewables, as mentioned. Although there would be emissions avoided in Morocco it is likely there will be consequential emissions elsewhere to meet the demand for hydrogen in the EU and elsewhere. These may be higher or lower than the avoided emissions in Morocco, depending on several factors.

9.2.4 Environmental, Social and Economic Factors

Hydrogen is planned to be potentially exported from Morocco via the Maghreb gas pipeline in future[209], which would limit the need to develop new infrastructure. This would limit a significant amount of embodied emissions related to new infrastructure projects.

Although heavily reliant on coal, the climate action tracker considers Morocco's climate targets and actions as almost sufficient[210]. In order to further enhance the country's policies and actions towards climate mitigation, the phase down of coal with international support alongside inhibiting further gas developments may be required. Overall, Morocco's policies, and action are in line with <1.5°C warming. To maintain and improve on

[209] https://www.moroccoworldnews.com/2023/07/356472/spain-italy-morocco-partner-on-green-hydrogen-export-venture
[210] https://climateactiontracker.org/countries/morocco/

these climate commitments it will be necessary for domestic decarbonisation to be balanced with green hydrogen production.

The unemployment rate in Morocco is reported to be 10.5%[211] and inequality is notable with the country having a gini coefficient of 39[212]. The poverty rate is reported as less than 9% of the Moroccan population[213]. To aid in improving the situation, any new developments should ideally aim to ensure socio-economic benefits are distributed amongst all stakeholders (through job creation, service delivery and local development).

9.3 FURTHER COUNTRY DETAILS

9.3.1 Projects powered by the grid

From data collected and analysed as part of this study, there are no announced projects in Morocco at feasibility stage or advanced that plan to use grid power.

9.3.2 Water Analysis

Morocco has an assortment of hydrogeological environments and therefore sources, due to its geological diversity. This also includes the Atlantic Ocean surrounding its western borders. As per Morocco's national water strategy[214], across the country, there's a varying amount of surface water, estimated at around 18 billion cubic meters in an average year. However, this amount can range widely, from as low as 5 billion cubic meters to as high as 50 billion cubic meters, depending on the year. The water situation is unpredictable because some years are very wet and others are extremely dry. About 67% of the renewable water resources come from surface water, and 33% comes from groundwater[215].

In Morocco, most of the water, about 85% (around 60-70% in dry years), is used in agriculture sector. Apart from that public water supply uses 12%, and industry uses 3% of the available water resources[216]. There is a current concern regarding the depletion of groundwater aquifers, resulting from low recharge rates and intense agricultural demand as a consequence of the expansion of this sector[217]. From the total water resources directed toward agriculture, approximately 40% of derived from groundwater sources[218]. Climate change induced warming is predicted to intensify this deficit further. Contamination is an additional stressor to the nation's groundwater, due to seawater intrusion and nitrate pollution from fertilisers and sewage. Lastly, water resource availability across Morocco is coming under pressure due to the pressure created on such systems from expanding populations and corresponding economic development[219]. Due to the mentioned hydrogeological diversity, systems with natural renewability of water resources exist and are expected to be strengthened and/or maintained if focused management is implemented[220].

In the future, climate change experts predict warming and reductions in rainfall in response to anthropogenic greenhouse gas emissions for the southern shore of the Mediterranean. There is a challenge in sourcing local freshwater toward the production of hydrogen without compounding the existing water stress. Morocco has over 2400 km of coastline thereby presenting the opportunity for seawater electrolysis thus reducing or removing the need for freshwater input. To ensure water security in Morocco, , such as Water Law 36-150 and National Water Sector Development Strategy encourage use of desalinated water to supplement traditional water sources, such as Water Law 36-150 and National Water Sector Development Strategy[221].

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[211] https://www.statista.com/statistics/502794/unemployment-rate-in-morocco/#:~:text=Unemployment%20rate%20in%20Morocco%202022&text=In%202022%2C%20the%20unemployment%20rate,decline%20of%20the%20unemployment%20rate.

[212] https://www.statista.com/forecasts/1165068/gini-index-forecast-in-morocco

[213] https://www.undp.org/arab-states/publications/poverty-arab-world-successes-and-limits-morrocos-experience#:~:text=March%2026%2C%202020&text=Today%2C%20less%20than%209%25%20of,to%2016.2%25%20a%20decade%20ago.

[214] National Water Strategy - Climate Change Laws of the World (climate-laws.org)

[215] Morocco | Water efficiency, productivity and sustainability in the NENA regions (WEPS-NENA) | Food and Agriculture Organization of the United Nations (fao.org)

[216] Slide 1 (un.org)

[217] *Moroccan groundwater resources and evolution with global climate changes (hal.science)*

[218] *Geosciences | Free Full-Text | Moroccan Groundwater Resources and Evolution with Global Climate Changes (mdpi.com)*

[219] *Assessment of Groundwater Quality: Impact of Natural and Anthropogenic Contamination in Souss-Massa River Basin | SpringerLink*

[220] *Water security and sustainable development (hal.science)*

[221] Managing Urban Water Scarcity in Morocco World Bank

9.3.3 Carbon feedstock requirements

Morocco does not have any announced e-fuel projects. It is a significant emitter of greenhouse gases with over 66 Mt CO_2 equivalent[222] emission in 2020, the majority of which comes from electricity generation since Morocco's energy supply is reliant on oil and coal. The main industries include phosphate, rock mining, and processing. These activities are not typically large emitters, which indicates low potential for capturing industrial emissions for use as carbon feedstock.

Morocco has opportunities for biogenic carbon sources with a remarkably high potential for use of biomass such as sugar cane and other agricultural waste or wood chips. Currently biofuels and waste biomass contribute to 6% in the total energy mix[223]. So, combination of direct air capture with biogenic CO_2 may work to provide a sustainable source for e-fuel production in the country.

9.3.4 Cumulative land and water requirements for planned projects that have an EU export focus in Morocco

The construction and operation of export scale hydrogen plants with co-located renewables can be considerable. In addition, water requirements for large scale electrolysis are extensive, but largely variable dependent on the water source and electrolyser technology. Ricardo's estimates for the total land and water requirements in Morocco, accounting only for projects included in the analysis of this study that have an EU export focus, are below:

Table 16 Total land and water requirements for planned projects that have an EU export focus

Supply Scenario	Km^2 required		Water Required Mt/y
100% Solar + Electrolysis plant	162.22	Equivalent to 15,020 football fields	4.4-6.6
100% Wind + Electrolysis plant	1116.37	Equivalent to 103,368 football fields	

9.4 OCP GROUP AMMONIA PRODUCTION FACILITY - TARFAYA

Hydrogen and renewable plant: OCP Group Ammonia Project will be built near Tarfaya in Morocco's south[224]. The production process will produce 200,000 tonnes of ammonia from 2026 with capacity expansion plans of 1 million tonnes and 3 million tonnes by 2027 and 2032 respectively. It will be powered with 1.2 GW of solar and 2.6 GW of wind energy and desalinated water will be used for electrolysis. The expected locations for solar and wind farms are Sebkha Tah and Laayoune.

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[222] https://data.worldbank.org/indicator/EN.ATM.CO2E.KT?locations=MA

[223] https://www.iea.org/countries/morocco

[224] https://www.ammoniaenergy.org/articles/ocp-group-renewable-ammonia-production-facility-planned-for-southern-morocco/

Figure 17 Plans for new renewable ammonia production facility (OCP Group)

Plant Footprint & Land Use: It is estimated that the total land requirement is 1490 km^2 for a 2.6 GW wind farm and for the 1.2 GW solar installation[225].

Social & natural value: Sebkha Tah is an area of great ecological value. Its location close to the Atlantic Ocean means the region has great potential for wind turbines and the difference in level between the ocean and the land offers the opportunity to produce electricity using hydraulic turbines. On the other hand, Laayoune is a new city present in Western Sahara, with a high solar potential, reflected in the 85 MW solar farm named Noor[226] which is present in the region. There is a natural oasis 19 km from the city, which provides the town with its water supply[227].

Analysis:

The coastal area for the hydrogen electrolyser, green ammonia plant, and desalination plant shown was analysed (Figure 17) and was established that it is in a region of desert with only basic transport infrastructure, with the only apparent port being in Tarfaya to the north. Project construction on undisturbed deserts will require numerous roads to be built to aid construction and ongoing operations. This could isolate species into fragments (so called habitat fragmentation), change habitats and introduce new invasive species[228].

The project does present opportunities to benefit communities as its plans state to oversize the desalination plant to provide clean water to the local municipality. As Sebkha Tah is the lowest point in Morocco[229] it may be more susceptible to rising sea levels in the future as the ocean encroaches on the land. This will place any infrastructure at this level at risk of failure or industrial accident and subsequently pollute the environment.

10. SUMMARY OF STRATEGIES, PROJECTS, AND EXPORTS

The following charts offer a summary of the national strategies, planned projects as per the database and the anticipated EU export quantity from the 6 discussed countries:

[225] Wind 85 acres/MW; Solar 3.5 acres/GWh/year Calculating Solar Energy's Land-Use Footprint (renewableenergyworld.com)
[226] https://acwapower.com/en/projects/noor-pv-1/
[227] Destination Guide to Visiting Laayoune in Morocco - MarocMama
[228] https://www.sciencedirect.com/topics/earth-and-planetary-sciences/habitat-fragmentation
[229] Environmental regionalization and endemic plant distribution in the Maghreb | Environmental Monitoring and Assessment (springer.com)

Figure 18 demonstrates the split between the stages of each of the projects within that country. From the identified projects, over 80% were at feasibility stage.

Figure 18 Volume of projects at various stages in each of the chosen countries

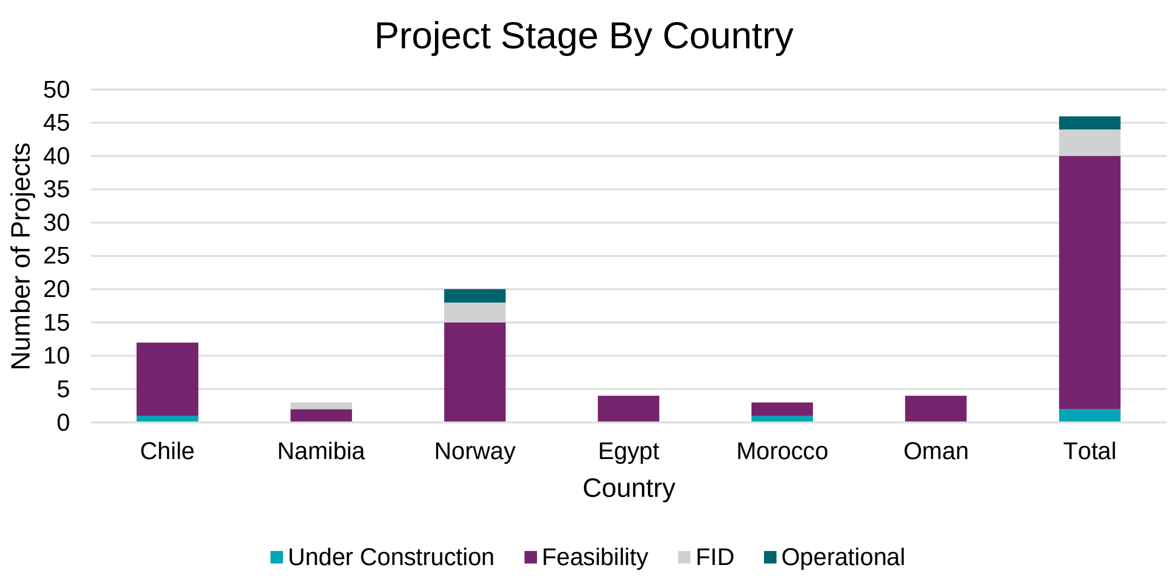


Figure 19 Summary of hydrogen strategies, planned projects and exports to the EU

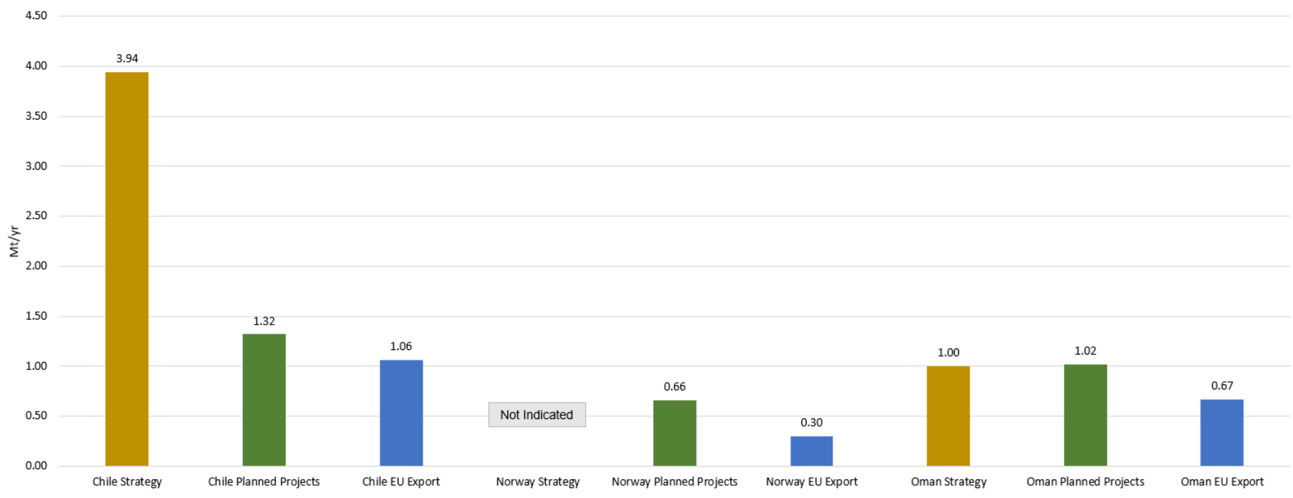
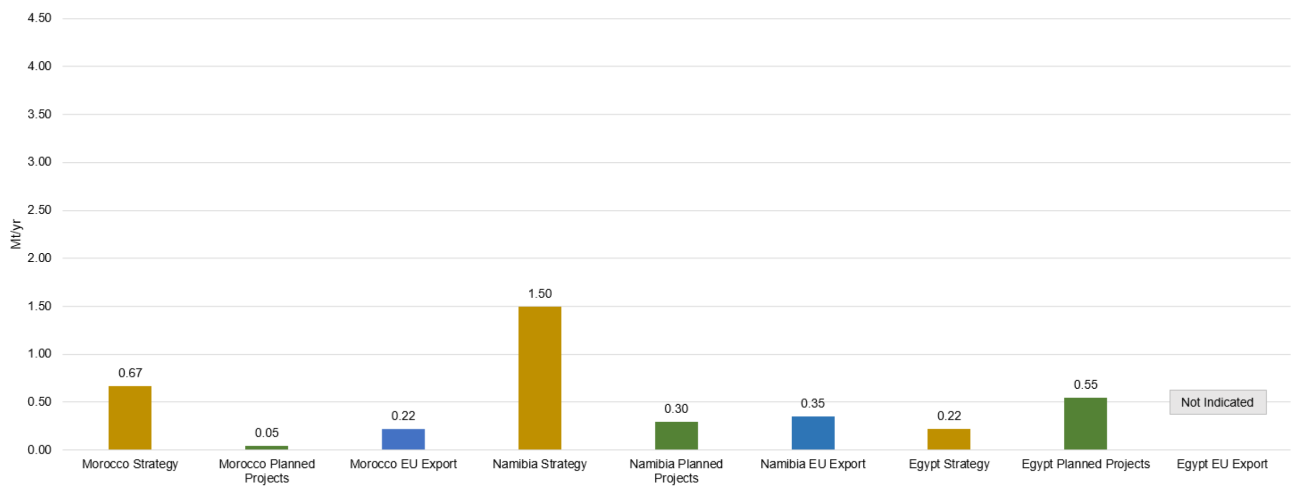
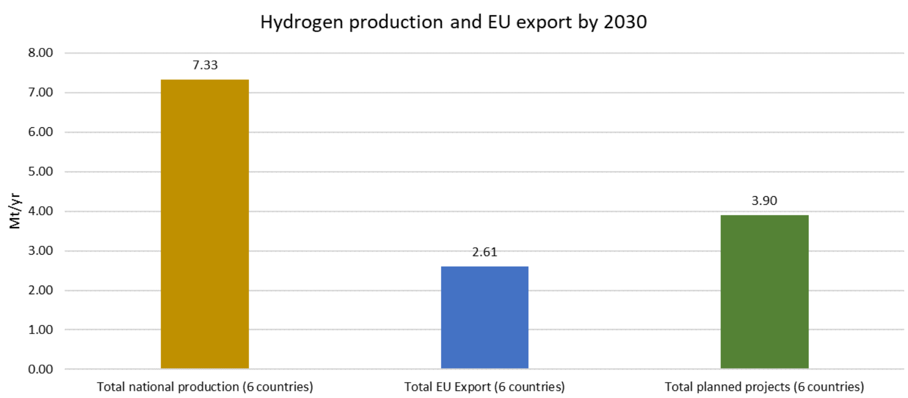


Figure 20 Summary of hydrogen strategies, planned projects and exports to the EU (continued)



The three countries with the largest national strategies are Chile, Namibia, and Oman. When considering planned projects, the three countries with the largest cumulative production are Chile, Oman, and Norway. Lastly, the countries with the largest anticipated exports to the EU are Chile, Oman, and Namibia. Based on production capacity for EU export, the most promising export nations appear to be Chile, Oman, Namibia, and Norway.

Figure 21 Cumulative national production, EU export and planned projects for the selected countries



The above figure shows that a potential 2.61 Mt/yr of hydrogen could be exported to the EU for the 6 countries discussed, which is significantly below the 10 Mt/yr ambition stated in REPowerEU. It is likely that other exporting countries in North Africa, North America, the Middle East, and Sub-Saharan Africa will contribute to deliver around this figure. Other projects may reach FID, increasing the potential supply to the EU, though this is uncertain and some projects will undoubtedly fail to reach the production stage.

Table 17 Summary of the detailed country analysis

Country	Opportunity	Hazard
Egypt	• Several projects are planning to export to EU • Respective renewable plants could decarbonise the fossil-fuel based grid	• Low availability of biogenic carbon sources • High water stress • Land competition in Suez and Mediterranean development zones
Oman	• Planned projects align with the country's hydrogen strategy • Opportunity for decarbonizing the country's grid network as projects plan to use either solar or wind power	• Low availability of biogenic carbon sources • Competition between decarbonization of grid and hydrogen development • Extremely high water stress • Relatively far from the EU
Norway	• Greatest number of planned hydrogen and e-fuel projects • Potential for hydrogen transport via pipeline • Decarbonised grid	• Lack of clarity about projects exporting green hydrogen to the EU • Consideration required for further extension of wind and hydro power plants • Large fossil fuel reserves make it more inclined towards blue hydrogen
Morocco	• Opportunity for boost of local economy with new plant development • Potential of hydrogen transport via pipeline, close to Southern EU • Excellent renewables resources	• Competition between decarbonization of grid and development of H2 • Lags behind the targets given in the strategy document • Water stress
Chile	• Ambitious targets in its strategy but lags behind with planned projects • New plans will use dedicated renewable energy plants	• It has high water stress • Greatest distance from the EU which will increase transport related emissions • May find it easier to export to Asia & Americas than EU
Namibia	• Relatively clean grid compared to neighbouring countries • New renewable plants can boost job creation and local economy • New desalination plants can provide portable water access to large population	• Less than half of population have access to electricity • Lack of policies and regulations, supporting green hydrogen development • Planned projects in key biodiversity area • Water stress near hydrogen projects

10.1 DISCUSSION OF IMPACTS ON EXPORTING COUNTRIES

The sections above demonstrate that the impacts of hydrogen export projects on exporting countries are complex, with potential benefits and detriments. There is an opportunity for international funding organisations to ensure that funded projects maximise these benefits and minimise potential downsides.

Potential downsides for exporting countries:

- Hydrogen projects may use renewables projects that could otherwise decarbonise the local electricity grid
  - This risk varies by project – while the Hyphen project in Namibia is far from any major population centre (the nearest town is only 20,000 inhabitants) meaning renewables there would have little benefit. The Masdar Hassan Allam projects in Egypt will be located near some of the more densely populated areas of the country, and are also near useful agricultural land, meaning renewables there could have local benefit.
- Funds that could be used for local-benefit renewables being diverted to export-focussed hydrogen projects
  - In most cases, export-focussed projects are funded by specific hydrogen funds, which would be separate from those targeting renewables projects. However, there may be some cases where country or regional specific funds might be used by hydrogen projects, which could potentially be to the detriment of local renewables
- The local skills and supply chain that could be used for local-benefit renewables being diverted to export focussed hydrogen projects
  - This may cause a delay to any large domestic renewables project. However, the build-up of local skills for international projects may leave a useful legacy for buildout of domestic renewables projects
- Developers flying in international workers to build and operate plants, rather than developing the local skills base, while using foreign equipment and materials. There is clear precedent for this, with this approach being used for many fossil fuel operations in the Global South.
  - This can be seen as a perpetuation of the extractive approach often seen today with oil and gas projects, where resources are appropriated with little local benefit
- Productive agricultural land being lost to solar farms or delicate environments being damaged by construction and infrastructure
- Exacerbation of existing water stress, or environmental impacts from desalination brine and electrolyser water polishing and cooling

Potential benefits for exporting countries:

- Large potential export value, with taxes contributing to the country, while government investment could create sovereign wealth funds
- Local jobs during construction and operation, with potential to develop the local supply chain, enabling future local-benefit renewables and decarbonisation
  - The Hyphen project plans for 15,000 jobs during construction and 3,000 during operation, and is targeting 90% of jobs fulfilled by local Namibians. An explicit aim of the OCP project is to develop a Moroccan supply chain for solar panels, wind turbines, electrolysers and batteries
- Several projects mention oversizing desalination plants to supply the local population with fresh water
  - An example of this is OCP, who will supply the town which is likely to house most of its workforce
- Excess electricity may support grid decarbonisation
  - Hyphen claims that excess electricity from hydrogen projects can decarbonise the entire Namibian grid
- Hydrogen produced by these projects may be consumed partly in-country, decarbonising industry or transport, providing a local benefit even for projects which do not contribute to the decarbonisation of electricity

11. BENEFITS OF PRODUCING HYDROGEN/E-FUELS DOMESTICALLY

11.1 DOMESTIC PRODUCTION: POTENTIAL EUROPEAN BUILD-OUT RATES

In this section we review whether Europe has the capacity to develop its own hydrogen industry to avoid the need for imports. In the REPowerEU analysis, 20Mt of hydrogen demand is modelled. 16Mt is associated with direct hydrogen use in the EU whether imported or produced domestically. The remaining 4Mt is associated with hydrogen derivative imports that will be used directly rather than converted back to hydrogen. Studies have shown that derivatives are more economical to produce in renewable energy rich regions and import than to produce domestically[230][231]. That leaves 6Mt of the 10Mt that is to be imported to be delivered either by pipeline or hydrogen carriers such as ammonia or LOHC. Here, the same studies show that pipelines are slightly more competitive with domestic production, but hydrogen carriers are not. At this time, it is not possible to quantify how much hydrogen could be imported by pipeline, therefore we consider the 16Mt of EU hydrogen production 2030 to be a best-case scenario for the European hydrogen sector.

11.1.1 Total renewable energy potential

The 2020 report "Renewable electricity requirements to decarbonise transport in Europe with electric vehicles, hydrogen and electrofuels" by Ricardo found that EU has approximately 20,430TWh of total renewable energy potential available to be exploited. Approximately 6,000TWh of that is required to support decarbonisation of the power grid. The remaining renewable energy potential leads to an estimated potential of up to 307Mt of hydrogen production potential. Although this shows that Europe has the potential to provide its own hydrogen needs, it does not consider build out rates that represent the feasibility infrastructure to be scaled up by 2030.

11.1.2 Realistically achievable domestic production

The 2021 European Hydrogen Backbone (EHB) report "Analysing future demand, supply and transport of hydrogen"[232] uses some of the same data sources with more constraining assumptions on EU rules and social acceptance to create an estimation of 11,100TWh per year of total renewable energy supply potential. Furthermore, they use a build out rate to suggest a deemed realistic renewable energy supply potential achievable by decade milestones. The study reaches a theoretical feasibility of hydrogen output of 450TWh achievable by 2030 after removing RE required for electricity decarbonisation, equivalent to 13.5Mt. This gives a rise to the justification of bridging the gap to the 16Mt pure hydrogen demand through importing.

The build out rate assumptions are influenced by the starting points and current trajectories of individual member states. A faster build-out rate could lead to heightened theoretical feasibilities of hydrogen output.

In December 2022 the IEA released a report reviewing whether the EU's policies were enough to achieve the needs of REPowerEU's decarbonisation plan. They found that policies at the time presented renewable energy uptake forecasts that fell short of what was required. The main case forecast found that renewable energy is expected to expand in the electricity system from 40% in 2022 to 55% by 2027. A linear projection of this forecasted progress shows that 61% electricity decarbonisation can be expected by 2030. 8% short of the 69% needed to power EVs, heat pumps and electrolysers.

The IEA shows that average solar PV build out rates of 39GWpa are not compatible with the 48GWpa that is required for REPowerEU under current policies[233]. However, the IEA states that 52GWpa can be achieved if existing member state solar-supportive policies were to be extended and member states currently not using them were to adopt them.

The EU wind build out rate is currently averaged at 16.9GWpa when the REPowerEU requirement is over double at 35.7GWpa. Unlike with solar, spreading best practice policies amongst member states does not solve the issue as the average build out rate is still deficient at 21.2GWpa.

Based on IEA's analysis, we estimate that 5.8 Mt of domestic production is achievable by 2030 in the main case and 7.5 Mt is achievable in the accelerated case[234]. This is higher than the volume of mandated hydrogen demand as identified in Table 1 but does not reach the 10Mt ambition of the REPowerEU plan.

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[230] https://iea.blob.core.windows.net/assets/acc7a642-e42b-4972-8893-2f03bf0bfa03/Towardshydrogendefinitionsbasedontheiremissionsintensity.pdf

[231] https://indiaesa.info/media/downloadfiles/2021-06-29_-_1H_2021_Hydrogen_Market_Outlook_A_Defining_Year_Ahead._904231958.pdf

[232] https://gasforclimate2050.eu/wp-content/uploads/2021/06/EHB_Analysing-the-future-demand-supply-and-transport-of-hydrogen_June-2021.pdf

[233] https://www.iea.org/reports/renewables-2022

[234] This was estimated by forecasting the level of wind and solar capacity constructed by 2030, calculating their renewable energy contribution and comparing it against what was required to achieve REPowerEU targets. It is based on the assumption that the renewable energy build out contributes to all relevant decarbonisation targets in a proportional manner.

11.1.3 Influencing developments

In December 2022[235], as a development of the REPowerEU plan, the EC agreed to amendments under the RED to accelerate permitting rules within “go-to areas”. Member states must adopt plans to designate these zones within 30 months of the amendment coming into force. The go-to areas would be chosen as particularly suitable areas for RE that present lower risks for the environment. Projects within the areas would be eligible for expedited consenting and limited against legal objection by being declared projects of overriding public interest. This may go some way towards increasing build out rates and enabling higher rates of renewable energy installation by 2030. It has not been indicated what scale these go-to regions will be and whether they will be enough to boost the renewable energy build out rate to satisfy the 69% renewable electricity decarbonisation requirement.

11.2 COST OF DOMESTIC PRODUCTION

The European Union member states have good renewable potential in the North Sea and Baltic Sea for offshore wind farms and the Iberian Peninsula with good solar and wind resources. To find out the cost of domestic production it is important to understand the renewable energy resources, land availability and infrastructure potential in different regions. A Belfer Center report stated that European countries including Croatia, Denmark, Estonia, Finland, France, Greece, Ireland, Latvia, Lithuania, Poland, Portugal, Spain and Sweden are resource rich with high infrastructure potential[236]. The analysis also revealed that Portugal, Spain, and France in the south, Ireland in the northwest, Finland and the Baltic States have potentials to fulfil domestic demand and emerge as regional exporters. As per optimistic scenario given in the IRENA report[237], Europe is predicted to have a levelized cost of hydrogen little less than 1USD per kg in 2050. Levelized cost of hydrogen (LCOH) is predicted for member countries with potential to become regional exporters given in Table 18. France, Spain, Portugal has the most competitive cost due to their wind energy potential whereas Romania and Hungary have high LCOH due to dependence on solar energy with lower capacity factor compared to wind energy[238].

Table 18 Summary of future LCOH in different locations in the EU as per supply and demand analysis

Location	Low LCOH ($/kg) [239, 240]	High LCOH ($/kg) [241]
Cyprus	2.70	3.10
Denmark	2.98	4.40
Estonia	3.37	4.20
Finland	3.82	4.23
France	0.99	4.42
Germany	1.10	1.75
Hungary	4.23	4.43
Ireland	3.18	4.00
Italy	0.99	1.60
Latvia	3.22	4.26
Lithuania	3.70	4.22
Portugal	0.89	3.67

[235] shortly after the IEA report was released
[236] https://www.belfercenter.org/publication/future-renewable-hydrogen-european-union-market-and-geopolitical-implications-0
[237] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Global_Hydrogen_Trade_Costs_2022.pdf
[238] https://www.nrel.gov/docs/fy15osti/63038.pdf
[239] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Global_Hydrogen_Trade_Costs_2022.pdf
[240] https://www.belfercenter.org/sites/default/files/files/publication/Report_EU%20Hydrogen_FINAL.pdf
[241] https://www.belfercenter.org/sites/default/files/files/publication/Report_EU%20Hydrogen_FINAL.pdf

Location	Low LCOH ($/kg) [239, 240]	High LCOH ($/kg) [241]
Romania	4.03	4.40
Spain	0.84	3.58

Iberian Peninsula

This peninsula in southwestern Europe is occupied by Spain and Portugal. In 2023 wind and solar reached record contributions to electricity in Spain, with 46% of electricity produced. Likewise, in Portugal solar and wind combined crossed 50% mark in total electricity. This peninsula presents opportunity for renewable hybrid projects, with capacity factor of up to 25% for solar energy projects[242] and up to 50% for offshore wind energy projects[243].

EDP Renewables has connected hybrid plant with grid including 8.4 MW of solar and 11 MW of wind power capacity, capable of producing 39.5 GWh annually[244]. Interconnection capacity of Iberian Peninsula is only 6%, which is lower than the target given in in the new regulation on the governance of the Energy Union[245]. To allow for greater trade between Peninsula and the rest of Europe, interconnection needs to be improved. There are many divergent views from the countries and energy companies on whether hydrogen or electricity is more suitable to transport energy in Europe. France, Spain and Portugal have backed under sea pipelines. Since the grid in undersized, hydrogen pipelines are debated to be a more cost-effective means of transmitting energy than electrical interconnects[246].

Based on the IRENA report[247], the levelized cost of hydrogen in both these countries could lie between 0.83USD per kg of hydrogen and 1.74USD per kg of hydrogen for 2050.

North Sea

The North Sea has some of the best offshore wind potential in the world thanks to its shallow waters and proximity to demand centres. Modern wind farms in the North Sea achieve a capacity factor of 45-55%. Manufacturers are developing taller and larger blade diameter turbines that are expected to achieve even higher capacity factors.

In 2022, in the same month as RePowerEU was published, EU country members Belgium, Denmark, Germany and Netherlands signed a declaration to produce 150 GW of offshore wind in the North Sea by 2050. In 2023, they collaborated with five other countries including non-EU countries Norway and the UK to develop at least 300 GW in the Northern Seas[248] by 2050.

In November 2019 Wind Europe released an influential report of how to deliver 450 GW of offshore wind across Europe by 2050[249]. The study recommended capacities for European countries including four declaration-founding EU countries as shown in Table 5. The high wind resource and shallow sea depths provide for particularly attractive Levelised Cost of Electricity prices (LCOEs). The very-low bracket corresponds with LCOEs of below €50/MWh whilst the low bracket corresponds with LCOEs of between €50/MWh and €65/MWh. This compares favourably with the average wholesale price of ~€2300/MWh seen across European economies in 2022 or the ~€104/MWh seen in 2021[250]. The study also found that relaxing current rules around exclusion zones would double availability of the most attractive seabed locations. The exclusion zones include space set aside for fishing, shipping and military activity or areas excluded for environmental reasons so added care would be required so as not to have any negative socioeconomic impacts.

242 https://greenalia.es/en/articles/greenalia-consolidates-its-solar-portfolio-in-spain-with-600-mw-with-grid-access/

243 The development of offshore wind power in Spain represents considerable progress in the energy transition | REVE News of the wind sector in Spain and in the world (evwind.es)

244 https://www.edpr.com/en/news/2023/01/12/edpr-commissions-its-first-hybrid-solar-and-wind-energy-park-iberian-peninsula

245 https://ec.europa.eu/commission/presscorner/detail/fr/MEMO_18_4622

246 https://www.ft.com/content/d21e39ff-0ded-4efc-b723-b85edb416532

247 https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Global_Hydrogen_Trade_Costs_2022.pdf

248 North Sea, Atlantic Ocean, Irish Sea and Baltic Sea

249 https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Our-Energy-Our-Future.pdf

250 Market analysis (europa.eu)

Table 19 Potential capacity for offshore wind in 2050 in European countries with access to the North Sea in GW

Country		Belgium	Denmark	Germany	Netherlands	Total
Target in GW		6.0	35.0	35.5	60.0	136.5
Current exclusions	Very low LCOE	3.7	6.1	12.0	33.4	55.2
	Low LCOE	2.3	28.9	23.5	26.6	81.3
Relaxed exclusions	Very low LCOE	4.9	22.9	31.1	60.0	118.9
	Low LCOE	1.1	12.1	4.4	0.0	17.6

Costs from hydrogen production powered by offshore wind with an LCOE of €40/MWh are expected to reach a minimum of €1.8/kg H_2[251]. Therefore, using an electrolysis efficiency factor of 71%:

- In the current exclusion scenario, it is expected that:
  - Up to 5.1 Mt of hydrogen could be produced at €1.8/kg H_2 to €2.8/kg H_2
  - Up to 7.6 Mt of hydrogen could be produced at €2.8/kg H_2 to €4/kg H_2
- In the relaxed exclusions scenario, it is expected that:
  - Up to 11.1 Mt of hydrogen could be produced at €1.8/kg H_2 to €2.8/kg H_2
  - Up to 1.6 Mt of hydrogen could be produced at €2.8/kg H_2 to €4/kg H_2

Hydrogen produced from very low LCOE power will be notably cheaper than the €3.7/kg H_2 calculated by the IEA to import hydrogen from North Africa to Germany by ship[252]. The cost of importing will depend on the availability of the European Hydrogen Backbone and its entry points, particularly in Spain, Italy, and Greece. At offshore wind LCOEs above €60/MWh importing becomes economically competitive[253].

Realistically, much of this power will be utilised directly as electricity to affordably decarbonise the power system of the EU. However, wind farms located further offshore can be penalised with higher power transmission costs, increasing their LCOE. There are proposals for a shared offshore grid that will decrease the cost for bringing the power to shore in a cost-effective manner. Offshore hydrogen production could also form part of the solution. Subsea hydrogen pipeline can be significantly more affordable than subsea power transmission cables, particularly over longer distances[254]. The hydrogen island concept[255] is an example of this solution and plans to install a 10 GW electrolyser to produce 1Mt of hydrogen to pipe to Germany and the Netherlands.

An integrated transmission pipeline is the core enabler to connecting these locations with points of demand and geological storage. Doing so provides the best opportunity of Europe becoming economically self-reliant for its hydrogen needs.

11.3 ECONOMIC BENEFITS

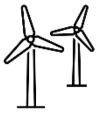
Developing a domestic hydrogen industry could provide a large increase of skilled green jobs not only in hydrogen production but also upstream in renewables implementation to provide the energy for hydrogen production. The Ukraine-Russia war has exposed the risks of being overly reliant on energy imports. Gas supply constraints and the resulting price volatility have brought challenging economic conditions to Europe's industry. Europe's decarbonisation plans aim to move away from fossil fuel dependence, reducing this supply risk[256].

In recent years, there has been a surge of policies, papers and announcements from governments and operators in the energy space in general, all linking through to hydrogen. As well as funding, a key component to delivering such significant change is proactively recognising the people with the right skills that need to be available to deliver innovation and change. Achieving the Net Zero ambition will require a transformation of

[251] https://cadmus.eui.eu/bitstream/handle/1814/73658/QM-01-22-010-EN-N.pdf?sequence=4&isAllowed=y
[252] Towards hydrogen definitions based on their emissions intensity (windows.net)
[253] https://iea.blob.core.windows.net/assets/e57fd1ee-aac7-494d-a351-f2a4024909b4/GlobalHydrogenReview2021.pdf
[254] https://www.pv-magazine.com/2021/03/19/hydrogen-shipping-vs-submarine-cables/
[255] https://hydrogenisland.dk/en
[256] Microsoft Word - D2.2 Skills Strategy 19 07 2023.docx (greenskillsforhydrogen.eu)

worker skills across many areas of the economy, particularly those working in buildings, transport, and energy itself.

The clear benefit of domestic production to local economies of the EU is the subsequent job creation across the supply chain, though investing both time and focus onto domestic production could potentially cascade through several aspects:



Decentralised Energy Production: Domestic production and offtake reduce reliance on centralised energy sources and therefore increases energy security by diversifying sources of energy supply.

Job Creation: Hydrogen production and offtake will require a significant uplift or transfer of EU jobs across the value chain. During the energy transition, the hydrogen industry could support workers from declining sectors that were at risk of significant job loss through direct and indirect jobs. The European Commission estimates that 20,000 jobs will be created per billion Euros of investment. In addition, a study by CIC EnergigGUNE estimated the creation of nearly 1 million jobs from green hydrogen by 2030, though this figure does not account for job creation via blue hydrogen and e-fuels[257] .

Trade Balance: The domestic production of hydrogen could encourage a better balance of trade in the EU than historically. As a result of the Russia-Ukraine war, the high cost of fossil fuels saw a EU bilateral trade deficit of $156 billion according to Brugel[258]. Decoupling from imported fossil fuel reliance would reduce the risk of price volatility as well as improved trade balance within the EU.

Economic Growth & Technological Innovation: In house manufacturing typically entails and facilitates research, development, and innovation. Companies and institutions that are engaged in commercial manufacturing are, particularly in an industry such as hydrogen, at the forefront of technological advancements. For this reason, countries with a stronghold of technological innovation and manufacturing capabilities drive economic competitiveness. Domestic production within the EU could enable an internal technological market that could reduce reliance on technological imports, reduce the associated scope 3 emissions of imported technology and increase supply chain resilience.

11.4 TYPES OF JOBS

As the global hydrogen industry advances, there will be the need for new roles as well as additional requirements of roles that are currently somewhat niche. Roadmaps and strategies are being released across the world with governments aiming to gain a better understanding of the required workforce to achieve set import, export, production, and end use targets. There will be a diverse range of jobs required, with workers requiring upskilling, retraining, or starting from zero. The diagram below shows some of the direct and indirect types of jobs and skills that will be required through to 2030:

[257] Betting on green hydrogen to fulfil employment growth | CIC energiGUNE
[258] The fiscal side of Europe's energy crisis: the facts, problems and prospects (bruegel.org)

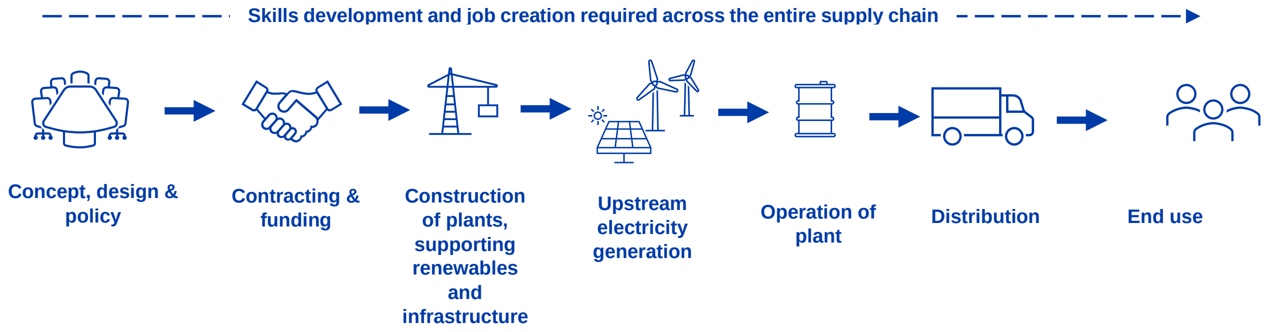


Figure 21 Areas of the supply chain that will require skill development and job creation with scale-up

Experience of hydrogen and hydrogen skills across the supply chain remains a niche area and the spread of relevant skills and experiences remains fairly small. In the wider economy, hydrogen is currently produced (largely grey hydrogen) and transported across Europe every day for use as an industrial gas. There are, therefore, already experienced professionals who have the skill set to move and use hydrogen, that have been safely and reliably doing so for decades. Such professionals have the relevant qualifications and experience for working with flammable gases.

11.5 INVESTMENT

For the hydrogen industry to achieve a scale up capable of domestic production to meet demand, significant investments are needed across the entire value chain. According to the 2023 Hydrogen Insights study commissioned by the Hydrogen Council, a group representing the industry, the total investment needed in line with a net-zero trajectory is $700 billion with a somewhat equal split required across end use and offtake, infrastructure, and production and supply[259]. Europe, as of the first quarter of 2023, is the global leader of hydrogen investment at $117 billion announced to 2030. Europe, as of the first quarter of 2023, is the global leader of hydrogen investment at $117 billion announced to 2030. According to the study, there is currently a $380 billion investment gap between announced direct investments and required investments to 2030.

11.6 POTENTIAL DISADVANTAGES FROM EU DOMESTIC HYDROGEN PRODUCTION

While there are significant potential benefits from the EU attempting to satisfy domestic hydrogen demand with domestic production, it should be acknowledged that there are potential downsides to such a strategy:

- Diverting investment in hydrogen projects to the already-wealthy EU from lower-income countries who could reap greater benefit from the investment and long-term income and employment
- Delay to decarbonisation of the EU electricity grid: Additionality rules ensure hydrogen production cannot consume existing renewables. However, it does not prevent hydrogen being produced from new renewables that would have been built anyway that could otherwise have decarbonised the grid. The capacity to build all the renewables needed for grid decarbonisation and hydrogen within the EU may be limited, meaning dedicated hydrogen renewables could further delay grid decarbonisation
- Due to having a higher population density and more productive farmland than the majority of the potential import countries, there may be greater conflict with land use and population for hydrogen produced in Europe
- The countries planning to export to Europe typically have greater renewables capacity factor and less seasonality than within the EU, meaning the payback time for the embedded carbon in production of the project, especially solar panels, will be worse for EU projects

[259] Hydrogen-Insights-2023.pdf (hydrogencouncil.com)

- Land and salaries are typically higher in the EU than the case study countries, which can increase the cost of a hydrogen project. This will however, likely be offset by lower cost of finance, cost of potentially longer supply chains and transport of the hydrogen itself

12. PRODUCTION AND TRANSPORT AND COSTS

12.1 SECTION OVERVIEW

This section critically assesses previous analysis on production and transportation of hydrogen within Europe (Spain) and compares it to production and delivery of hydrogen from North Africa (Morocco to Marseille).

12.2 HYDROGEN TRANSPORTATION

Current production and use of hydrogen is largely close coupled with hydrogen production facilities located close to offtakers. Consequently, the cost the end-user pays is usually close to the cost of production. The hydrogen economy as envisaged considers production of green hydrogen in resource rich areas (wind, solar) with hydrogen then transported to offtakers.

There are several options considered feasible for transport of hydrogen, however, it is generally more difficult to move about than traditional fuels such as natural gas. The key methods of bulk transport at international level are:

- Transport of gaseous hydrogen via pipeline
- Transport of liquid hydrogen via tanker ships
- Transport of hydrogen derivatives (ammonia, LOHCs) via tanker ships

Transport by road and rail is also feasible but is mostly considered for distribution rather than for transmission.

Key benchmarks when considering transport vectors are safety, technical feasibility, and economic viability. Ammonia for example is a commodity which is traded internationally in bulk today with well-established infrastructure and supply chains. While this makes it a strong contender for transporting hydrogen, the conversion from hydrogen to ammonia and back to hydrogen is energy intensive and requires costly processing plant to achieve. Gaseous hydrogen is not constrained in this manner, but its volumetric energy density is so low that it cannot reasonably be transported by ship. Liquid hydrogen could in future see delivery by tanker ship but would have to make around 2.5 deliveries to match the energy supplied by a single tanker of LNG.

12.3 PRODUCTION COSTS OF HYDROGEN

The economics of hydrogen production is most often framed in terms of levelized cost. Levelized costs attempt to account for total plant costs (both capex and opex) including engineering, civils, labour, insurance, plant equipment, electrical grid upgrades, as well as raw material costs over the plant lifetime. Methodologies used to generate levelized costs are almost always similar, with the difference in final costs down to assumptions and forecasts.

Green hydrogen plants of a fixed size will see some variability in construction costs depending on where they are to be built, but differences in these costs are usually small when compared to overall plant lifetime costs. The prime driver in the levelized cost of hydrogen is typically the cost of the electricity used to produce it. The cheaper it is to generate electricity, the cheaper it will be to produce hydrogen.

For optimised economics, based on the studies below, the production cost of hydrogen from solar PV in Spain is expected to fall to the region of 2.1-3.5 USD/kgH_2 by 2030, while the production cost of hydrogen from solar PV in North Africa is expected to fall to the region of 1.9-3.2 USD/kgH_2 by 2030.

Table 20 Summary of LCOH for 2030 in Spain and Morocco

Source	Author	Year(s) Analysed	Levelized cost of Hydrogen Spain ($/kg H_2)	Levelized cost of Hydrogen Morocco ($/kg$H_2$)
Site-specific, comparative	Fraunhofer ISE	2030	2.1 - 2.5	2 - 2.5

Source	Author	Year(s) Analysed	Levelized cost of Hydrogen Spain ($/kg H_2)	Levelized cost of Hydrogen Morocco ($/kg$H_2$)
analysis for suitable Power-to-X pathways and products in developing and emerging countries[260]				
Towards hydrogen definitions based on their emissions intensity[261]	IEA	2030	N/A *	1.9 - 2.6
Renewable Hydrogen Imports Could Compete with EU Production by 2030[262]	Aurora Energy Research	2030	N/A	3.2
Contrasting European hydrogen pathways[263]	Oxford Institute for Energy Studies	2030	3.4	N/A
Enabling the European hydrogen economy[264]	Aurora Energy Research	2030	2.5 - 3.5	N/A

*NW Europe costs given as ~3.4 to 4.7 USD/kg but not considered representative of Spain.

The levelized cost of hydrogen from solar PV is very similar in Spain and Morocco and aligns with the price ranges from other regions with excellent solar irradiation such as Australia, China, Chile and the Middle East. Plant capital costs are largely similar, so the main differentiator is the cost of electricity from solar PV. While solar energy yields are slightly higher for Morocco than for Spain, the advantage is marginal.

The low-end costs of ~2 USD/kg make favourable assumptions about the price of electrolysers in 2030, with costs ranging from approximately 20-30% of 2021 costs. While these costs are oft repeated in literature, this is considered overly optimistic due to current demand for electrolysers greatly outstripping supply, with scale-up unlikely to offset this bottleneck in the near-term. This constraint applies equally across geographies and so will have a similar impact on LCOH from both countries.

While Morocco possesses marginally better solar resources than southern Spain, its wind potential is significantly stronger. While most analyses put the LCOH from solar roughly equal, if Morocco's wind resources are properly leveraged in tandem, it will likely be able to produce slightly cheaper low-carbon hydrogen than Spain. Ultimately, the main impact on cost of the final delivered hydrogen will be driven by cost of transportation.

12.4 TRANSPORT COSTS OF HYDROGEN

Three methods of transport have been considered in delivery of hydrogen to Marseille from Morocco:

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[260] files.h2-global.de/H2G_Fraunhofer-ISE_Site-specific-comparative-analysis-for-suitable-Power-to-X-pathways-and-products-in-developing-and-emerging-countries.pdf

[261] Towards hydrogen definitions based on their emissions intensity – Analysis - IEA

[262] Renewable hydrogen imports could compete with EU production by 2030 | Aurora Energy Research (auroraer.com)

[263] Contrasting-European-hydrogen-pathways-An-analysis-of-differing-approaches-in-key-markets-NG166.pdf (oxfordenergy.org)

[264] Enabling the European hydrogen economy (auroraer.com)

- A new 48” subsea pipeline to tie-in with European hydrogen backbone. The pipeline will run from the region around Tarfaya up to Tangiers and across the strait of Gibraltar to Tarifa. See Figure 22.
- Shipping of liquefied hydrogen from Tarfaya, to the LNG Terminal at Fos Cavaou, west of Marseille. See Figure 23.
- Shipping of ammonia from Tarfaya, to the LNG Terminal at Fos Cavaou, west of Marseille. See Figure 23.

The Moroccan **pipeline length** is taken as 35 km offshore & 1325 km onshore (1360 km total), while the **shipping route** is estimated at 2590 km.

For transport of Spanish hydrogen, it is assumed that the European Hydrogen Backbone is used. As this study has not reviewed siting for a Spanish green hydrogen production facility, a pipeline length of 100 km has been selected to allow for comparison.

The levelized cost of hydrogen has been taken as 2.0 $/kgH_2$ for Spanish production and 1.8 $/kgH_2$ for Morocco.

Figure 22 Potential subsea pipeline route from Tangiers to Tarifa (illustration only)

Figure 23 Potential overland pipeline through Morocco and shipping route to Marseille (illustration only)

An uplift to the LCOH has been applied and is exclusive of the financial impacts of the Barcelona to Marseille (BarMar) pipeline.

For sake of equal comparison, a 48" pipeline has been modelled, as this was the most commonly modelled within literature. For more accurate modelling, the actual pipeline would have to be sized based on required energy flows which are not known at this time. As 48” is the largest pipeline diameter typically used in gas transmission systems within Europe, it provides an upper limit to financial estimates. OPEX costs vary by source but are consistently in the region of 1-3% of CAPEX annually. The pipeline is assumed to have a 40-years operational life. Good agreement is found across most literature on pipeline costs – mostly because it is a well-established and simple technology.

Table 21 Transmission pipeline costs and impact on LCOH

Source	Moroccan Pipeline costs ($m)	Moroccan LCOH Uplift ($/kg$H_2$)	Moroccan Final LCOH ($/kg$H_2$)	Spanish Pipeline costs ($m)	Spanish LCOH Uplift ($/kg$H_2$)	Spanish Final LCOH ($/kg$H_2$)
Fraunhofer ISE	2180*	1.8	3.6	150*	0.14	2.14
European Hydrogen Backbone[265]	4200**	3.6	5.4	305**	0.28	2.28
Hydrogen 4EU[266]	3820 - 5130**	3.9	5.7	275 - 370**	0.31	2.31
Ricardo	3080 - 6160	3.6	5.4	220 - 450	0.28	2.28

* Costing was completed for 36 cm (14”) pipeline. A scaling ratio of 2.4 has been applied to account for larger diameter, based on industry experience.

**Costs provided were only for onshore pipelines. A scaling ratio of 1.8 has been applied to account for offshore section, based on industry experience.

Transport of bulk chemicals by ship is common practice with oil, LNG, LPG, and ammonia being some of the most traded commodities worldwide. The largest LNG carriers in the world have a maximum transport capacity of over 260,000 m^3 but more typical sizes are around 135,000 m^3 with costs in the region of $170 million per ship[267][268]. LPG and ammonia ships are far smaller, bulk carriers usually in the region of 80,000 m^3 for LPG and costing around $70 million per ship[269]. Ammonia tankers tend to be smaller still, in the region of 35,000 m^3 and costing $50 million per ship.

Transport of hydrogen by tanker ship is not currently undertaken at scale. The Susio Frontier is the only liquefied hydrogen carrier in operation today and has an operating capacity of 1,250 m^3 and cost reported at $355 million. Liquefied gas carriers benefit from economies of scale, and strong savings can be expected from technology learning rates. With future ship sizes expected in the region of 160,000 m^3, costs might optimistically begin to reach the region of $450 million.

Prior to and after shipping, both ammonia and LH_2 must be treated. Ammonia is produced from hydrogen in the Haber-Bosch process, which operates at high temperatures and pressures, and then is cooled to -33.3°C at atmospheric pressure to liquefy it. It is then shipped, and can be reconverted to hydrogen via cracking, again at high temperatures. Ammonia can be directly used in various chemical processes or potentially for power generation and green steel production.

Liquid hydrogen is obtained by cooling hydrogen to -253°C. This process is energy intensive, often requiring about 1/3 of the total energy capacity of the hydrogen to be liquefied. Given the cryogenic temperatures and complexity of the process, even small-scale hydrogen liquefaction can easily cost tens of millions of dollars. Reconversion to gaseous hydrogen is a more straightforward process and far cheaper but can still entail significant costs.

[265] EHB#2_report_part1_210614.indd (gasforclimate2050.eu)

[266] Charting Pathways to Enable Net Zero (hydrogen4eu.com)

[267] Different type and sizes of Liquefied natural gas (LNG) carriers (maritimeoptima.com)

[268] Secondhand LNG carrier prices hit record high; prospects rosy - KED Global

[269] Different types and sizes of Liquefied petroleum gas (LPG) carriers (maritimeoptima.com)

Table 22 Ammonia shipping costs and impact on LCOH

Source	NH_3 export conversion cost uplift ($/kgH$_2$)	NH_3 shipping cost uplift ($/kgH$_2$)	NH_3 cracking cost uplift ($/kgH$_2$)	Total LCOH Uplift ($/kgH$_2$)	Moroccan Final LCOH ($/kgH$_2$)
Fraunhofer ISE*	-	-	-	4.10	5.90
European Hydrogen Backbone	0.46	0.04	0.25	0.75	2.55
Hydrogen 4EU	1.68	0.44	1.98	4.10	5.90

* Costing assumes a mix of solar PV & wind with final delivery to Germany and no ammonia cracking. A derating factor of 0.8 has been applied to account for differences in modelling.

Table 23 Liquefied hydrogen shipping costs and impact on LCOH

Source	LH_2 export conversion cost uplift ($/kgH$_2$)	LH_2 shipping cost uplift ($/kgH$_2$)	LH_2 gasification cost uplift ($/kgH$_2$)	Total LCOH Uplift ($/kgH$_2$)	Moroccan Final LCOH ($/kgH$_2$)
European Hydrogen Backbone	0.99	0.06	0.11	1.16	2.96
Hydrogen 4EU	2.23	1.20	1.43	4.86	6.66

The European Hydrogen Backbone costs are considerably lower than those suggested by other analyses. By its own admission, the methodology is very optimistic, assuming significant scale-up and technology development not available in the near-term. For example, their assumed cost of a liquid hydrogen carrier of 160,000 m^3 is approximately $200 million, which may not be achievable even by 2050 without radical advances in material science and liquefaction processes. Even with these extremely optimistic assumptions, shipping hydrogen over such short distances does not stack-up economically when compared to more local production and integration with an existing transmission network.

The Fraunhofer and Hydrogen 4EU costs show good alignment with wider global shipping and pipeline prediction costs published elsewhere. The Fraunhofer results have been adjusted to account for differences in renewables make-up, final delivery port and reconversion costs. Even without this adjustment the total cost is still of a similar magnitude to that calculated within Hydrogen 4EU, which would be expected.

12.5 CHAPTER CONCLUSIONS

Transport of hydrogen from Morocco is clearly most cost effective via pipeline. The upfront costs are expensive when compared to a single gas carrier ship but likely to be more cost effective over a longer time frame.

Given the significant uplift to levelized cost, shipping of liquefied hydrogen or ammonia from Morocco is unlikely to be cost-competitive with hydrogen produced in Spain by 2030.

While transport by pipeline from west Morocco does not appear to be cost competitive with hydrogen generated in Spain, there is significant cost entailed by the overland pipeline running within Morocco. As modelled, the Spanish hydrogen costs benefit disproportionately from the exclusion of the Hydrogen Backbone pipeline costs. If these were accounted for, transport by pipeline from Morocco might become cost-competitive although this is highly likely to be dependent upon project specifics. The economics also do not account for benefits that might be realised at a local level by this infrastructure investment such as job creation, and how this might be maximised.

Table 24 Final LCOH with delivery to Marseille

Hydrogen source	Transport option	LCOH Production ($/kgH$_2$)	Transport cost uplift ($/kgH$_2$)	Final LCOH ($/kgH$_2$)
Spain	Pipeline	2.0	0.28	2.28
Morocco	Pipeline	1.8	3.60	5.4
Morocco	Ammonia shipping	1.8	4.10	5.9
Morocco	LH$_2$ shipping	1.8	4.80	6.6

13. CONCLUSIONS

The Russia invasion of Ukraine has brought into focus some of the risks of a global energy market, with gas supply constraints and the resulting price volatility placing great strain on Europe’s industry. A reduction in Europe’s reliance on natural gas will be a natural consequence of decarbonisation. However, by seeking to import a significant proportion of its future energy in the form of hydrogen and derivatives, there is a potential supply risk of continued reliance on foreign energy supply. Many of the countries likely to export hydrogen to Europe are in the Global South, leading to concerns about resource exploitation, environmental impacts and delaying local decarbonisation. This report finds that this is a complex situation without simple right or wrong answers. There are benefits and risks associated with the EU importing hydrogen, both to the exporting countries and to the EU itself. This presents a challenge for international funders and project developers, as their hydrogen projects could entrench existing inequalities or be of benefit to the producing country. The key findings that will affect any projects are as follows:

Most plants will be located in remote locations with no urban settlements. The footprint of hydrogen production is not considerable, though when considering the capacity factor for renewable energy plants, they need to be sized 2.5 to 5 times the electrolyser capacity and the space requirement will be huge. Since there are no trees in expected renewable energy plant locations in desert countries, the establishment of these plants doesn't require deforestation.

Most countries in the study have high to very high water stress and it is expected to rise further in the future due to climate change impacts in addition to most being desert countries (except Norway). However, a few nations, like Chile and Morocco, have long coastlines while others, like Namibia and Oman, have few coastal cities with seawater readily available. Desalination can be used to cover for the hydrogen production. Norway does not have risk of water stress and its complete population has access to portable water in the country.

Desert countries lack biogenic sources for carbon feedstock from farming waste or forestry residues. These nations will need to use either on industrial emissions or direct air capture for their carbon requirements. Countries cannot rely only on capturing emissions from fossil fuelled power plants industrial emissions as these will not be eligible as e-fuels in future. Countries with agricultural waste can use biogenic carbon sources, potentially along with direct air capture. Although the underutilization of agricultural waste presents an opportunity to use since these countries have low biomass usage as compared to the total agricultural waste generated, though it is worth noting that some biogenic sources are more sustainable than others.

The 6 countries analysed have varying electricity systems in terms of size and emissions intensity. The hydrogen strategies, planned projects (which are mainly at feasibility stage and have significant uncertainty with regards to success), and planned exports highlight differing challenges and opportunities within the various contexts. Further, the socio-economic realities of the different jurisdictions also vary, with some having the opportunity to capitalise on new industries to better the economic status quo. The following summarises the key conclusions from the country analysis:

Egypt’s electricity generation as of 2022 was 167TWh, with 89% coming from fossil fuels and 100% electricity access. In 2030 the electricity demand is expected to increase to 180TWh and 52% of this will be fossil based. In order to produce the 2030 target of 0.22Mt/yr of green hydrogen, an equivalent of 6% of the 2030 electricity generation would be required. If renewables originally meant for green hydrogen were reprioritized for grid decarbonisation, a decrease of 7.2% in electricity emissions would be seen. Consequential emissions may arise elsewhere due to this reprioritisation. Egypt, based on its policies and action, is set for an emissions trajectory that would contribute to warming of between 2°C and 3°C. The 0.55Mt/yr H_2 of planned projects up to 2030 already exceed the Egyptian hydrogen strategy of 0.22Mt/yr H_2. It is unclear at this point how much hydrogen will be exported to other jurisdictions. These activities could drive economic activity by creating jobs and local development. With unemployment levels at 7%, there is an opportunity for hydrogen to help in this regard.

Oman’s electricity generation in 2020 was 38TWh, with 99% of the generation coming from fossil sources and the population having 100% electricity access. It is forecasted that by 2030 the electricity demand will be 40TWh, with 70% of this coming from fossil sources. If 0.67Mt/yr of green hydrogen is produced, the expected export amount to the EU by 2030, these renewables could decarbonise 84% of the grid highlighting a potential conflict between hydrogen production and grid decarbonisation. In this case, a decrease of 88% in electricity emissions would be seen, though there would be the potential for consequential emissions in another location. Oman’s hydrogen strategy outlines a hydrogen production ambition of 1Mt/yr by 2030, which aligns closely with the planned projects. The expected EU export of 0.67Mt/yr would require shipping which currently would imply significant Scope 2 emissions. Considering Oman's poverty levels of 10.4%, the green hydrogen economy could bring about jobs and local economic benefit which may improve some socio-economic aspects.

The electricity supply of **Norway** in 2022 was 146TWh, with only 2% of this coming from fossil sources and the country having 100% electricity access. By 2030 it is forecasted that the electricity supply will be 173TWh. Norway's hydrogen strategy does not state an ambition for the national hydrogen production capacity by 2030. The planned projects by 2030 could produce about 0.66Mt/yr and 0.3Mt/yr is expected to be exported to the EU. In order to produce 0.3Mt/yr of green hydrogen by 2030 for EU export, this would imply an increase of 10% to the electricity supply in 2022. This would likely be in the form of wind or hydro. If renewables originally meant for EU export green hydrogen were reprioritized for grid decarbonisation, the grid could be fully decarbonised and hydrogen could still be produced with the remaining generation. Although this is possible, it may lead to consequential emissions elsewhere to meet the EU's hydrogen shortfall. Norway's policies and actions are almost aligned with <1.5°C warming and is overall socio-economically stable. This said, Norway's fossil fuel production still contributes significantly to global emissions. Green hydrogen production could further enhance Norway's economy and decarbonisation efforts.

Morocco's electricity generation, as of 2022, was about 41TWh and 63% of this was from fossil fuel sources. Morocco has a particularly emissions-intensive grid of 610gCO_2/kWh, given a large reliance on coal and gas. Nonetheless, 100% electricity access is reported. By 2030, electricity demand is expected to increase to 77TWh. In order to produce 0.22Mt/yr of hydrogen, the expected EU export quantity by 2030, 27% of the 2022 electricity supply would be required. This could displace fossil fuel production if there was an opportunity for reprioritisation which would avoid 42% of the electricity emissions as of 2022. This said, it is expected that there would be consequential emissions elsewhere alongside those avoided in Morocco. Morocco's hydrogen strategy projects 0.67Mt/yr hydrogen production by 2030. Currently, the production capacity of the planned projects at or beyond FID is 0.05Mt/yr, highlighting a clear deficit between ambition and tangible progress. Although having a highly emissions intensive grid, Morocco's policies and actions particularly with regards to coal power phase-out align with warming of <1.5°C. Poverty (<9%) and inequality (gini coefficient of 39) are significant in Morocco, both of which could potentially benefit from the income from hydrogen projects.

Electricity generation in 2020 was 71TWh in **Chile**, with 52% of this coming from fossil fuels. It is projected that by 2030 the electricity generation will increase to 88TWh, with 44% of this coming from fossil fuels. To produce the hydrogen planned to be exported to the EU (1Mt/yr), this would require 50TWh of renewable generation (58% of the 2030 demand). This could potentially displace all fossil generation, and the remaining generation being used for hydrogen production. This may lead to consequential emissions elsewhere if the EU makes up the hydrogen shortfall. Decarbonisation is needed as Chile's ambition and policies are currently not aligned with <2°C warming. Chile's hydrogen strategy plans 3.94Mt/yr hydrogen production by 2030. Planned projects at FID or beyond may cumulatively produce 1.32Mt/yr, less than half of the government's ambition. There is significant inequality (gini of 44.9) and levels of poverty (11.5%) in both of which have the potential for improvement from export-focussed hydrogen projects.

Namibia imports 60% of its total electricity supply (4.55TWh) and less than 50% of its population has access to electricity. Although the installed capacity in Namibia is largely renewable, the imported electricity is mostly coal generated from South Africa, with very high associated carbon emissions. In order to produce the reported EU export amount of 0.35Mt/yr of hydrogen, 17.5TWh of renewable generation would be needed which is 10 times the installed generation of Namibia in 2020. This could fully decarbonise the grid, eliminate dependence on fossil based imports and produce green hydrogen. However, this strategy may lead to consequential emissions elsewhere. Therefore, there is a conflict between grid decarbonisation and hydrogen production (though some hydrogen projects claim their excess electricity generation will be used to decarbonise the grid). The Namibian hydrogen strategy has a production ambition of 1.5Mt/yr whilst planned projects are currently one fifth of this at 0.3Mt/yr. There are significant levels of inequality (gini coefficient of 59.1), unemployment (21%) and multi-dimensional poverty (43%) in Namibia. As such, any investments in the country have the potential to improve conditions for local communities if well managed.

A potential 2.6Mt/yr of hydrogen could be exported to the EU from the 6 countries discussed, which is significantly below the 10Mt/yr ambition stated in RePower EU. Countries such as the USA, South Africa and Saudia Arabia are also expected to export to the EU, reducing this shortfall. It is likely that other projects will reach FID soon, increasing the potential supply to the EU. However, it is also likely that some projects will fail to reach the production stage.

The impact of hydrogen export projects on exporting countries is complex, with potential benefits and detriments. There is an opportunity for international funding organisations to ensure that funded projects maximise these benefits and minimise potential downsides.

Potential risks for exporting countries include:

- Hydrogen projects using renewables projects that could otherwise decarbonise the local electricity grid; Funds, skills and supply chain that could be used for local-benefit renewables being diverted to hydrogen projects; Developers using international workers to build and operate plants, while using foreign equipment and materials; Agricultural land being lost to solar farms, delicate environments being damaged or increasing water stress.

Potential benefits include:

- Export income increasing national wealth; Local jobs during construction and operation, which could develop the local supply chain for future domestic renewables; Desalination plants could supply the local population while excess electricity can support grid decarbonisation; Hydrogen produced by these projects may be consumed partly in-country, decarbonising industry, or transport.

Producing hydrogen within the EU for domestic consumption has many advantages, which include:

- Enabling benefits of high renewable potential in the North Sea and Iberian Peninsula to extend beyond these regions; Lower transport and distribution costs (both financial and environmental) of hydrogen; Job creation, improved balance of trade and technology leadership; Reduced risks associated with import of energy; Lower overall energy requirement and fewer losses compared to sea routes and hydrogen carriers.

Potential downsides from EU domestic production include:

- Diverting valuable foreign investment from lower income countries to the EU; Delaying EU grid decarbonisation due to limited availability of renewables; Conflict with land-use and population; Higher lifecycle emissions due to lower (solar) capacity factor; Higher land and labour costs.

The supply chain risk for hydrogen is rather low considering the anticipated domestic production and future hydrogen storage in the EU.

This study finds that mass import of hydrogen from beyond the EU may not be cost competitive with hydrogen produced within regions of the EU with strong renewable potential. Morocco possesses some of the best overlapping wind and solar resources in the world and is positioned well geographically to support hydrogen demand in Europe. Even with these advantages, the lack of transport infrastructure and the cost entailed in its development presents a major challenge. Further investment is required in this area if hydrogen is to effectively support the energy transition, and further study is necessary to assess the feasibility of different solutions and identify those which are both cost-effective and equitable.

The dynamics of supply and demand, and the uncertainty therein, are also likely to shape the future of the import and export markets. While many entities are interested in the supply of hydrogen, the demand currently does not exist and investment, leadership and support are missing at government and state levels.

Recommendations for further work

Given the challenges within the EU related to the rate of renewables roll-out and hydrogen projects progressing, it is recommended that a stocktake be performed on the findings within the 2020 report "Renewable electricity requirements to decarbonise transport in Europe with electric vehicles, hydrogen and electrofuels" by Ricardo for T&E. This will help to understand whether the EU is still on-track to meet its hydrogen demands or will have to rely on imports and the challenges this would entail.

There is a possibility that the EU will not be able to import its targeted volumes of hydrogen, either from failure of projects to progress or countries choosing to prioritise domestic decarbonisation and electricity access over hydrogen production and export. It is recommended that a study be performed to determine whether the EU could meet this shortfall, how it might do so, and what the environmental impact would be of various hydrogen production scenarios.

This report shows that while there are many potential benefits for countries planning on exporting hydrogen to the EU, especially those in the Global South, these benefits are by no means guaranteed. If the economic interests of international developers are allowed to dominate, there may instead be environmental and socio-economic downsides. It is recommended that Transport & Environment work with relevant stakeholders and experts to draw up a list of guidelines or requirements for governmental or institutional funders to ensure projects focussed on export to the EU consider equitable outcomes and avoid exploitation. Publication of such guidelines may also encourage offtakers to consider the broader sustainability of hydrogen they procure.

APPENDICES

APPENDIX 1 HYDROGEN TRANSPORT EMISSIONS

Emissions per year = EF * length of journey * deadweight + EF * length of journey * (weight of hydrogen + deadweight)

Hydrogen transport emissions calculation – Chile

Parameter	Unit		Comment
Emissions factor	$gCO_2/t.km$	16.3	Emissions factor
Length of journey	km	15000	Length of journey
Amount of H_2 transported	t	1000000	Amount of H2 transported
Emissions in one year	$kgCO_2eq$/journey	2.93E+08	Emissions in one year

Hydrogen transport emissions calculation – Oman

Parameter	Unit		Comment
Emissions factor	$gCO_2/t.km$	16.3	Emissions factor
Length of journey	km	10000	Length of journey
Amount of H_2 transported	t	670000	Amount of H2 transported
Emissions in one year	$kgCO_2eq$/journey	141810000	Emissions in one year

Hydrogen transport emissions calculation – Namibia

Parameter	Unit		Comment
Emissions factor	$gCO_2/t.km$	16.3	Emissions factor
Length of journey	km	11709	Length of journey
Amount of H_2 transported	t	1000000	Amount of H2 transported
Emissions in one year	$kgCO_2eq$/journey	2.29E+08	Emissions in one year

APPENDIX 2 DATA SUPPORTING SUPPLY CHAIN CALCULATION

Technical capacity of entry points (EP_m)

The technical capacity of border entry points was taken from data given by the European Network of Transmission System Operators for Gas association.

Table 25 Data from transmission capacity map 2021

Number	Point	Arc	Technical physical capacity (GWh/d)
200	St. Fergus	NO>UK	705.8
201	Dornum (EPT1 & EPT2)	Y-NOd>	575.9
202	Emden (EPT1)	Y-NOp>	1,481.5
203	Emden (NPT)	Y-NOp>	356.0
204	Zeebrugge ZPT	>IB-BEhz	488.0
205	Dunkerque	>IB-FR2	570.0
206	Easington	NO>UK	793.3
207	Tarifa	DZ>ES	442.7
208	Almería	DZ>ES	289.0
209	Mazara del Vallo	>IB-ITi	1,138.1
210	Gela	>IB-ITi	475.8
211	Imatra	RUeu>FI	220.0
213	Kotlovka	BY>LT	325.4
214	Tieterowka	BY>PL	7.3
215	Kondratki	BY>PL/YAM	1,027.1
216	Wysokoje	BY>PL	169.1
218	Uzhgorod (UA) - Velké Kapušany (SK)	UA>SK	2,028.0
221	Isaccea (RO) - Orlovka (UA) I	RO>UAe	122.2
		UA>RO	201.9
	Isaccea (RO) - Orlovka (UA) II	UA>RO/TBP	293.3
	Isaccea (RO) - Orlovka (UA) III	UA>RO/TBP	297.4
222	Kipi (TR) / Kipi (GR)	>IB-GRk	48.6
223	Värska	IB-RUen>	35.7
224	Greifswald	Y-RUg/NOS>	1,742.0
		IB-RUen>	0.0
226	VIP Mediesu Aurit - Isaccea (RO-UA)	UA>RO	370.8
228	Dornum GASPOOL	Y-NOd>	153.2
229	Lubmin II	RU/NO2>DEg	962.4

Number	Point	Arc	Technical physical capacity (GWh/d)
230	GCP GAZ-SYSTEM/UA TSO	PL>UAe	0.0
		UA>PL	135.6
231	VIP Bereg (HU) / VIP Bereg (UA)	HU>UAe	0.0
		UA>HU	515.6
232	Strandzha 2 (BG) / Malkoclar (TR)	TR/STR>BGg/BGT	576.0
233	Kipoi	TR/TNP>GR/TAP	350.0
	Total		16,897.7

Maximum storage deliverability (S_m)

Report[270] contains the combined withdrawal rate for EU27 and the UK given in the table below

Table 26 EU27 and the UK

Type of storage	Depleted reservoirs	Aquifers	Salt caverns
Total working gas capacity (TWh)	792	170	206
Total max withdrawal rate (TWh per day)	10.7	2.7	8.4
Rate of Withdrawal (per day)	1.4%	1.6%	4.1%

UK has a gas volume of 1.5 billion cubic meters, which is taken out from total storage deliverability to find storage deliverability in the EU.

Table 27 Gas storage facilities in the UK[271]

Facility	Estimated working gas volume (mcm)	Maximum production rate (mcm/day)
Hornsea	285	12
Hatfield Moor	70	2
Humbly Grove	243	7
Aldbrough	205	31
Holford	237	22
Hill Top Farm	59	13
Stublach	400	30
Total	1509	117[272]

[270] Guidehouse GIE - Picturing the value of underground gas storage to the European hydrogen system

[271] https://www.ofgem.gov.uk/sites/default/files/docs/2021/01/2021_gas_storage_data_0.pdf

[272] Total technical storage deliverability is 4212 TJ

APPENDIX 3 LAND USE ASSUMPTIONS

If for a particular hydrogen production plant the nature of renewable energy plant is known and the size of renewable energy installation is not given then following assumption were made to find out the land use for renewable energy plant:

- Footprint for wind energy plant is 85 acres/MW and solar energy plant is 123 acres/MW
- Solar and wind contribution in total required electricity to power the electrolyser plant is equal
- Solar capacity factor is 20%
- Wind capacity factor is 20%

APPENDIX 4 WATER USE ASSUMPTIONS

The following assumptions have been applied when calculating water requirements for hydrogen:

- 20 – 30 l/kgH_2 is required to make hydrogen
- 0.0025 Mt of water is equal to one Olympic sized swimming pool

APPENDIX 5 AVOIDED EMISSIONS ASSUMPTIONS

Assumed emissions intensities for fossil generated power sources

Type of Fossil Generation	Emissions intensity (gCO_2/kWh)
Gas	450
Coal	950
Oil	750

Assumed fossil generation mix for the 6 study countries[273]

Country	Gas	Coal	Oil
Chile	37%	38%	25%
Norway	100%	0%	0%
Oman	100%	0%	0%
Egypt	90%	0%	10%
Morocco	28%	60%	12%
Namibia	28%	72%	0%

Calculated emissions intensities for fossil generated electricity in the 6 study countries

Country	Emissions intensity (gCO_2/kWh)
Chile	717
Norway	450
Oman	450
Egypt	480

[273] https://openinframap.org/stats was made use of where fossil generation mix was not clear

Country	Emissions intensity (gCO_2/kWh)
Morocco	786
Namibia	894

Relevant equations in avoided emissions calculation:

Avoided emissions = Emissions Intensity*Electricity required to produce EU export H_2 in country X

Total emissions = Emissions Intensity*Fossil Generated Electricity in country X

% Decrease in emissions = (Avoided emissions / Total emissions) * 100

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