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MENA region as a potential hydrogen supplier for the European market: analysing a prospective route between Kingdom of Saudi Arabia and Germany

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Nomenclature

RE	Renewable Energy
GCC	Gulf Cooperation Council
KSA	Kingdom of Saudi Arabia
PV	Solar Photovoltaic
CF	Capacity Factor
AHP	Analytic Hierarchy Process
GIS	Geographic Information System
PVOUT	The amount of electricity that can be generated from the installed PV capacity in one location in one year (kWh/kWp)
IEC	International Electrotechnical Commission
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen
AEP	Annual Energy Production
CAPEX	Capital Expenditures
CRF	Capital Recovery Factor
OPEX	Operational Expenditures
NIMBY	Not in My Back Yard
MENA	Middle East and North Africa
EU	The European Union

1. Introduction

Several sectors are expected to decarbonize their activities via using renewable energies in the form of electricity or green hydrogen. The advantage of green hydrogen is that it can be stored and transported like any industrial gas or physical commodity. Hence, hydrogen as an energy carrier can overcome the obstacles associated with the intermittent renewable energy resources. However, envisaging a sustainable hydrogen supply chain is linked with other types of challenges. First, the process of transforming renewable energy (RE) into green hydrogen is costly and there are various techno-economic options and wide uncertainties. Second, transportation and storage of hydrogen incur considerable costs and encounter various challenges. Third, the renewable resources are abundant in certain regions (Betak et al. 2012) and regional supply does not always match demand (DFD and DFR 2022). Therefore, sophisticated logistical systems are required to store and transport the generated hydrogen. Besides the high costs, such systems can be also designed in different ways and can be influenced by several techno-economic, geopolitical and legal factors.

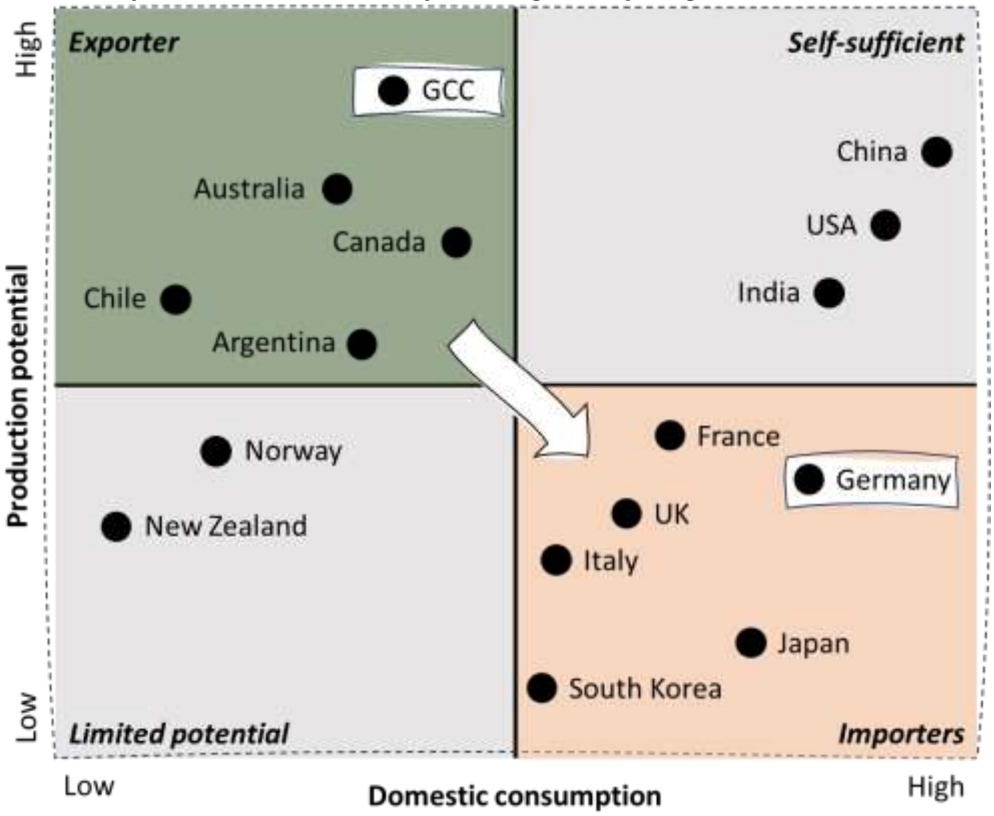
Based on the availability of renewable energy and domestic consumption, a matrix can be derived to show the position of different countries (see Figure 1). Herein, countries can be classified into four categories: exporter, importer, self-sufficient and limited potentials (IRENA 2022; DFF and DFR 2022). For example, despite the national and European plans to extensively expand renewable energy capacities in the coming three decades, the projected demand is not expected to be covered solely from regional supplies. As can be seen in Figure 1, the major European economies lie in the 'importer' area. Some studies expect the European hydrogen demand to exceed 100 million tons (Seck et al. 2022). The analyses of (Weichenhain et al. 2021) however estimate lower demand of 45 million tons of which 40% will be satisfied via imports.

The size of this gap is not the same across Europe due to regional variances in terms of industrial activities and population densities. For example, Western Europe (specifically Germany) is expected to have the highest demand (Andreola et al. 2021). According to the German national hydrogen strategy (BMWi 2020), Germany will not be able to satisfy its green hydrogen demand by depending on its renewable resources. Consequently, the necessity for imports becomes imperative. Notably, Germany allocated recently approximately 3.5 billion EUR for green hydrogen imports between 2027 and 2035 (Alkousaa 2024). On the contrary, countries with enormous renewable energy (RE) resources are anticipated to have surplus energy supplies that can be used for hydrogen exports. For example, the MENA region is expected to be an important supplier of green hydrogen due to the abundance of its renewable resources (IRENA 2021a). In the recent years, several memorandums of understanding (MOUs) and declarations of intents have been signed between different stakeholders from Europe and MENA region (Piotrowski and Salame 2023). Also, several potential projects have been announced and initiated.

Recognizing the need to secure hydrogen supply chains, Germany has been fostering a proactive hydrogen diplomacy to strengthen its relationships with the potential hydrogen exporters. For example, two recent studies between Germany and Kingdom of Saudi Arabia (KSA) and the United Arab Emirates (UAE) have emphasized the potentials and importance of such trading routes due to the considerable differences in green hydrogen production costs in Germany versus the Gulf region (Schimmel et al. 2022; Schröder et al. 2021). Nonetheless, this notion can't be generalised to assess the whole supply chain. First, the focus should not be only on the production cost at the supply point, as conversion and transportation are associated with inefficiencies and additional costs. Also, the production costs are not the same everywhere and at all scales. Thus, it is important to verify the available information, consider externalities, define the suitable production locations, and take additional costs of conversion and transportation into account. Therefore, the question should rather be: what is the cost of hydrogen (or its derivatives) at the consumption point?

Against this background, the aim of this paper is to study the potential hydrogen route from the Gulf region (KSA) to Europe (Germany) from a techno-economic perspective. This route is interesting for various reasons. Firstly, the Gulf Corporation Council (GCC) boasts the highest production potentials within the ‘exporter’ area (Figure 1), while Germany leads in domestic consumption and holds significant production capabilities within the ‘importer’ category. Hence, this assessment can establish a foundation for an examination of production and trading value chain dynamics. Secondly, as pioneering actors, Germany and KSA play pivotal roles in shaping strategies and ambitions that will influence the global supply chain's trajectory. Thirdly, Germany's unwavering commitment to achieve carbon neutrality matches KSA's endeavour to diversify its economy and energy sources. Additionally, the GCC's robust financing mechanisms and existing infrastructure, coupled with Germany's determination to decarbonize, underscore the potential for establishing hydrogen supply chains.

Figure 1: Matrix of production vs. consumption of green hydrogen



Source: Revisualized based on DFF and DFR, 2020

The analyses aim at incorporating the relevant upstream and downstream operations that can impact this supply chain and its costs. From the supply side, the associated costs of production and transportation should be analysed. For the demand side, the quantities and consumers should be analysed. Moreover, the competitiveness of the prospective trading route should be also contrasted with other potential options and suppliers. The policies and geopolitical aspects relevant for the establishment of this value chain should be also examined.

Hence, this paper addresses several questions:

- What is the competitive advantage of KSA to be a reliable hydrogen supplier to Germany?
- What is the cost structure and the impact of configuration on the supply chain?
- What is the trade-off between production costs, conversion, and transportation?
- What is the role of location and production scale?
- Would the total costs be competitive enough, compared with other potential suppliers?

2. Green hydrogen production costs: a comprehensive analysis of the Saudi Arabian context

2.1 Renewable energies and electrolysis plant

Renewables energies currently contribute approximately 30% to the global electricity production (Ritchie and Rosado 2020). This share should reach to 90% by 2050, of which solar and wind energies will provide more than two thirds (IEA 2021). The high deployment rates of renewable energies resulted in increasing the maturity of the relevant technologies and decreasing costs. For example, the capacity, efficiency, and rotor size of wind turbines have increased over time contributing to lower levelized cost of energy (LCOE). The cumulative capacity of wind energy has increased more than 10 times in the last 15 years (See Figure A1, Appendix I). Within the same period, the LCOE of onshore wind has also decreased by two thirds. Similarly, the cumulative installed capacity of solar energy has increased approximately 1000 times in the last two decades (Figure A2, Appendix I). Within the same time frame, the cost of PV module decreased from more than 5 USD/W to less than 0.5 USD/W.

Nonetheless, renewable energies are intermittent, and their availability varies based on the time throughout the day and year. The location also has an impact as the intensity of solar and wind energies are not the same everywhere. Hydrogen presents itself as an attractive solution to decouple the usage of renewable energies from the location and time of energy production. Hydrogen is currently produced mainly from fossil resources via steam reforming (grey hydrogen). The current global production is approximately 120 Mt (Collis and Schomäcker 2022), which is mainly used as a feedstock for industrial operations. The green hydrogen is produced differently. The carbon-free power is firstly produced from renewable resources such as solar and wind energies. The generated renewable electricity is then used to decompose the water molecules into hydrogen and oxygen (electrolysis), which is why the produced hydrogen is also carbon-free.

Electrolysis is the second major step along the supply chain of green hydrogen. Electrolyzers can be designed based on different physiochemical and electrochemical concepts (IRENA 2020). The current focus is on four major types: Alkaline electrolyser (AEL), Polymer Electrolyte Membrane or Proton Exchange Membrane (PEM) electrolyser, Anion Exchange Membrane (AEM) electrolyser, and Solid Oxide electrolyser (SOEC). AEL and PEM have higher technological maturity than AEM and SOEC. Each technology has its own advantages and disadvantages. For example, some can operate at high pressures but need some critical materials and expensive components. Estimating the accurate costs is also challenging due to the paucity of existing industrial-scale projects which gives rise to inconsistencies in the literature, and thus it is unusual to encounter analogues figures in the different studies. That's why carrying out a techno-economic comparison is challenging. The lack of industrial-scale projects is also a manifestation of the low technological maturity. Therefore, the costs are expected to decrease as the Technology Readiness Level (TRL) increases. For example, the study of (Reksten et al. 2022) expects that the PEM electrolyser with a capacity of 10 MW would decrease by more than 50% in the coming few years (Figure A3, Appendix I). Such crucial change is not expected in the production costs of solar and wind energies as they have developed a learning curve over the last decades (Satymov et al. 2022). This time dimension has a considerable impact on the prospective supply chain as discussed later.

2.2 Production costs of renewable energies and green hydrogen in KSA

The cost of renewable energy represents a decisive factor in the production cost of green hydrogen. Although there is no consensus regarding the cost break down of the hydrogen production due to the different assumptions and parameters, various studies attribute more than 50% of the cost to the electricity (Nigbur et al. 2023). Hence, using affordable renewables is mandatory to drive costs down. In this regard, certain countries and regions, which are endowed with good renewable resources, have a competitive advantage in the prospective supply chain of green hydrogen.

There are various factors that can impact the generation of wind and solar energies. For example, they can be directly related to the energy content (e.g. wind speed, air density, irradiation, etc.) or indirectly impact the performance and efficiency of the relevant technologies (e.g. weather conditions, dust, etc.). Overall, the capacity factor can be used as a proxy for the potential of solar and wind energies in a certain area. Capacity factor (CF) denotes the ratio between the actual electrical energy produced by the plant divided by the rated capacity (i.e. the maximum amount of energy that can be produced at full capacity) (Bolson et al. 2022).

While the CF is important in determining the economics of energy production, the location suitability depends on additional factors. For example, the proximity to the power network and roads and lower slopes are favourable conditions for the prospective RE parks. Hence, the quantitative analyses have considered the relevant factors that can impact the suitability of certain area for RE production (i.e. capacity factor, railway, roads, power grid, slope, and population). Because the factors are of different nature and have dissimilar units, mathematical operations (e.g. summation and multiplication) cannot be carried out directly. Hence, a multi-criteria decision analysis approach (Analytic Hierarchy Process – AHP) has been used to rate the suitability of different locations for installing wind and solar plants.

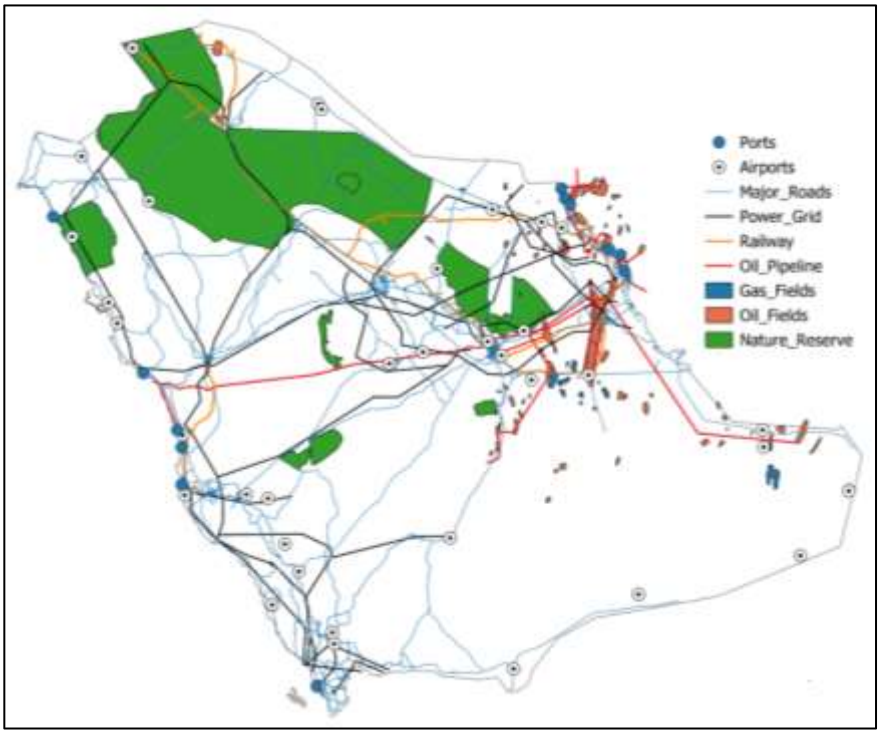
A Geographic Information System (GIS) model has been developed to provide data for the quantitative analyses. For example, the availability of solar and wind energies has been analysed via integrating the GIS of solar and wind capacity factors as raster layers. In terms of solar energy, the average annual full hour capacity has been used. For wind energy, the average hourly capacity factor was added. Due to the large area of KSA, the raster maps have been transformed into vector (grid) maps with a cell size of 5km*5km. Each cell takes the average value of the raster data it contains. The relevant datasets that have been collected and integrated into the GIS are listed in Table 1 in Appendix II.

Based on the average value in each cell, a score from 0 – 5 is given to represent the suitability of this location regarding the respective parameter. For example, cells with the highest wind capacity factor got the highest suitability score (i.e. 5), and vice versa. Each parameter is also given a certain importance (weight) value, which is then used to determine the total suitability score of each pixel (Eq. 1 in Appendix III). For each cell, S denotes the total suitability score, C_i refers to the score of criterion i, and W_i represents the weight given for each criterion. The bands of suitability scores as well as the significance of each parameter have been estimated based on literature and personal estimation. A similar approach has been also adopted by (Gharaibeh et al. 2021).

Cells with score 0 have been excluded, such as natural reserves, areas with a very high proximity to the infrastructure system or very high slopes (> 15°). The wind capacity factors of different classes (IEC I, II and III) have been acquired from the Global Wind Atlas (GlobalWindAtlas 2023). For solar energy, the raster maps of PVOUT were obtained from Global Solar Atlas (GlobalSolarAtlas 2023). PVOUT denotes the amount of electricity that can be generated from the installed PV capacity in one location in one year (kWh/kWp). Both (Global Wind Atlas and Global Solar Atlas) projects provide high-resolution data that can be used to assess wind and solar resources all over the world. The population density data is based on the dataset of Kontur (400-m resolution) (Kontur 2023). The raster maps of slope data are based on NASA Shuttle Radar Topography Mission (SRTM) and have been acquired from (OpenTopography 2013). The power grid network was added based on (Mahdy et al. 2016). The data of roads, railway, airports, land use and nature reserve were sourced from Open Street Maps (OSM) (OSM 2023). Herein, only major roads have been considered in the model[1]. Figures 2 – 4 depict the data after processing in GIS (also Figures A4 – A6 in Appendix I).

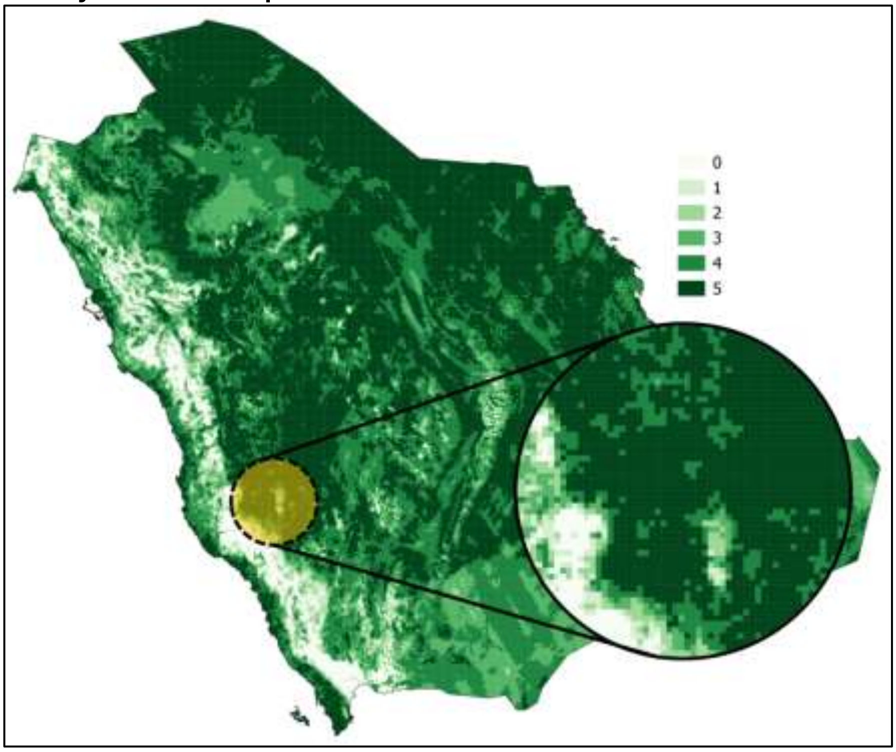
[1] OSM tags: highway=motorway, highway=trunk, and highway=primary.

Figure 2: Infrastructure and land-use in KSA



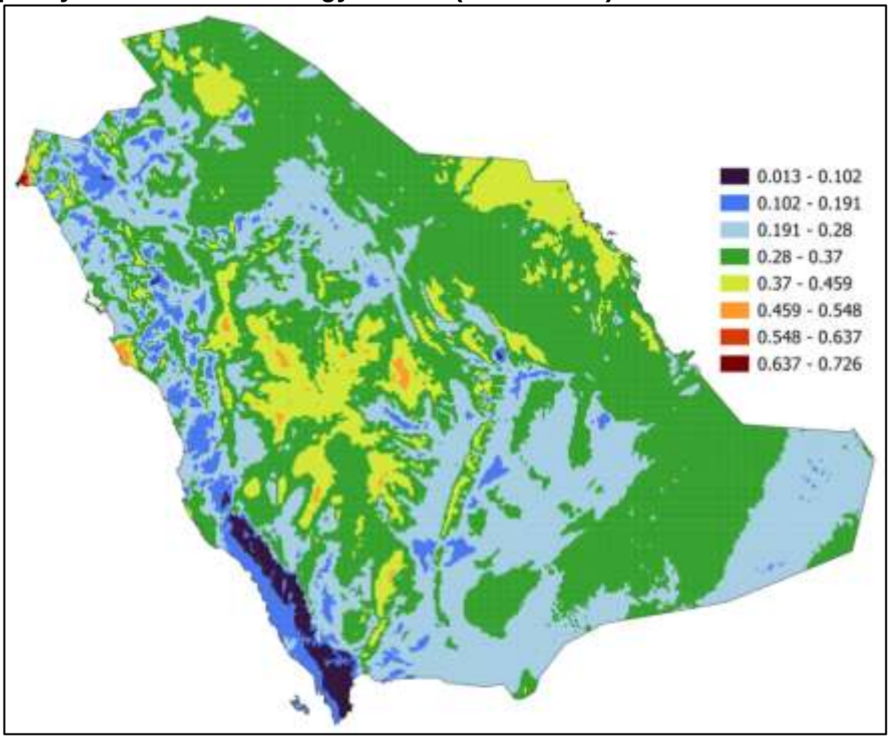
Source: Visualised based on (Mohammed Hamidaddin et al. 2017; GPF 2016; Mahdy et al. 2016; Ali 2023; WPS 2023; IC-SA 2023)

Figure 3: Suitability scores of slope



Source: Own analysis and visualization based on (OpenTopography 2013)

Figure 4: Capacity factor of wind energy in KSA (class: IEC I)



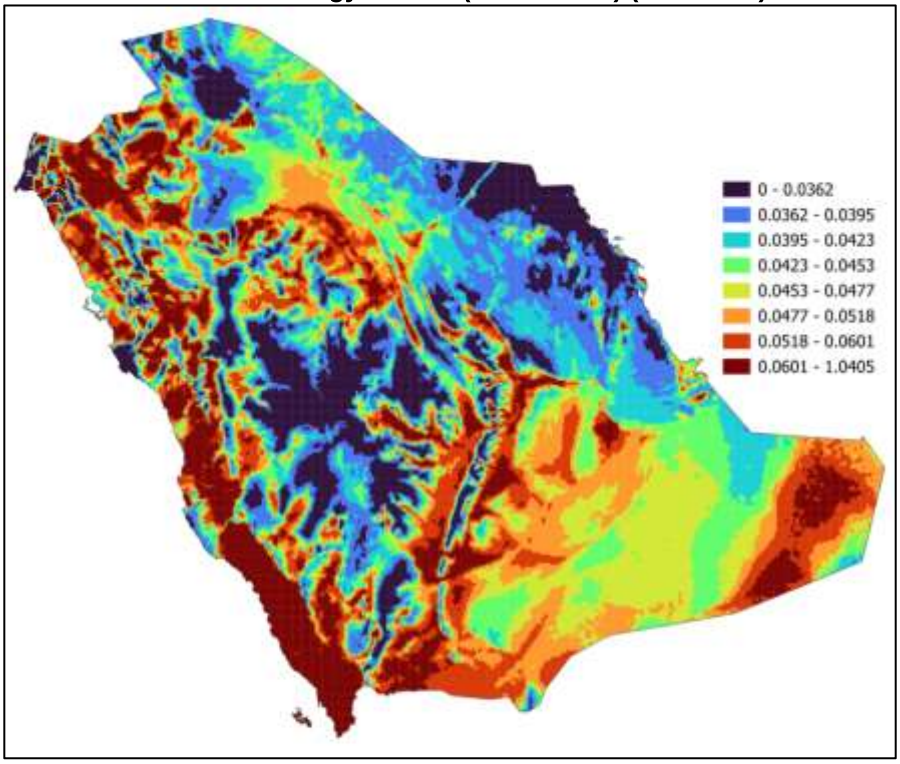
Source: Own analysis and visualization based on (GlobalWindAtlas 2023)

The cost calculations have been carried out based on (Rhodes et al. 2017). Eq. 2 – eq. 4 in Appendix II show the calculation procedures of the capital recovery factor (CRF), levelized cost of energy (LCOE) and annual energy production (AEP), respectively. For solar photovoltaic, a capital cost of 665 EUR/kW and a lifetime of 30 years have been considered based on (Kost et al. 2021) (Class: utility-scale > 1 MW). For OPEX, 1.5% CAPEX has been assumed based on (Erichsen et al. 2019). Based on the height and mean wind speed, the wind turbines are classified into three classes (IEC I, II and III) (Roach et al. 2020). The CAPEX and OPEX of the different wind turbines' classes are based on (Satymov et al. 2022) (See Figure 7, Appendix 1). The lifetime (25 years) and interest rate (7%) have been used based on the same study. For the electrolyser, there are various assumptions regarding the electrolyser's lifetime (Yates et al. 2020). This study considered a 25-year lifetime.

The levelized cost of wind and solar energies are visualized in Figures 5 and A8 in (Appendix I). Comparing the LCOEs of solar with the LCOEs of wind shows that variance of solar is low (all values range between 0.03 – 0.04 EUR/kWh), which is not the case in wind. Hence, solar parks can be built anywhere, while the locations of onshore wind parks have to be selected carefully. For verification, the calculated costs have been compared with the numbers in the literature, such as the study of (Kost et al. 2021). The maps of suitability scores are depicted in Figures 6 and A9 (Appendix I).

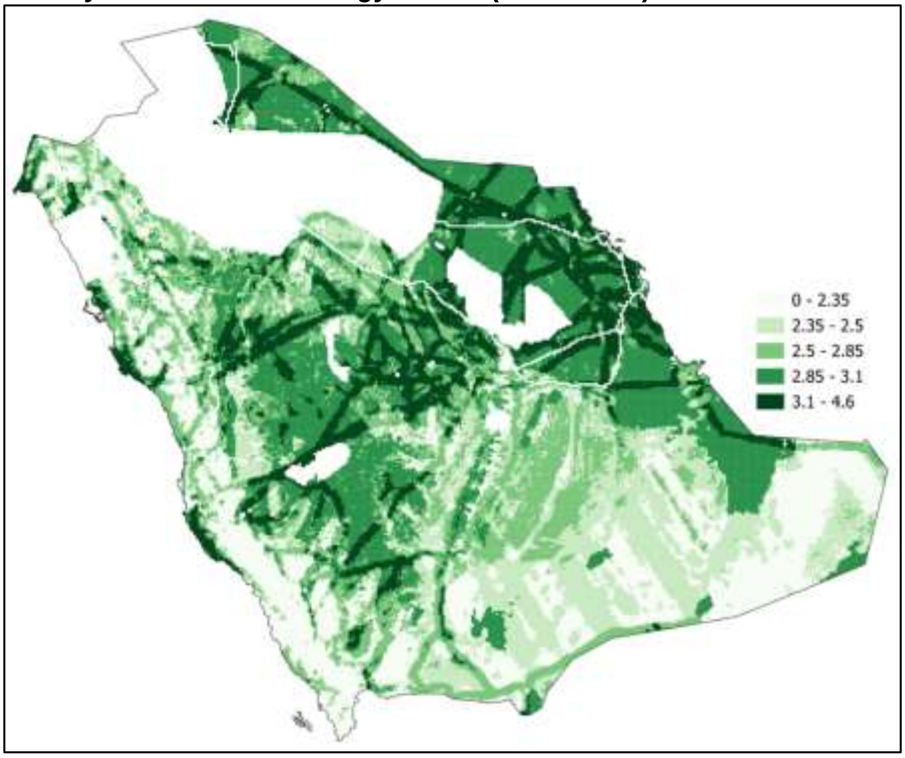
The levelized cost of hydrogen (LCOH) is calculated based on eq. 5 – eq. 10 in Appendix III. The direct capital costs are calculated based on Figure A3 (Reksten et al. 2022). Besides the direct CAPEX, there are other indirect CAPEX that include import, construction, engineering, licensing, and contingency. Herein, these costs are assumed to be 50%, based on (Ali Khan et al. 2021). Also, the fixed OPEX is assumed 6.25% of the direct CAPEX. The variable OPEX consists of water, electricity, and stack replacement. We assume that the stack cost equals 20% of the direct CAPEX with a lifetime of 40,000 operating hours. One kilogram of hydrogen requires approximately 10 litre water. We assume the water is sourced via desalination with a cost of 3 EUR/m^3 (Swisher et al. 2019). Hence, the cost of specific water consumption = 0.03 EUR/kg H_2. We consider an energy content of 33.3 kWh/kg H_2 (Andersson and Grönkvist 2019). As the current electrolyser's efficiency is 65%, 51.32 KWh will be required for each kg of hydrogen. If we consider the highest wind CF (0.726) and lowest LCOE (0.02 EUR/kWh), we end up with the LCOH of 4.28 EUR/kg H_2. If we consider a lower CF (0.4), the LCOE will increase to 0.033 and LCOH will reach 4.91 EUR/kg H_2.

Figure 5: Levelized costs of wind energy in KSA (class: IEC I) (EUR/kWh)



Source: Own analysis and visualization based on (GlobalWindAtlas 2023; Rhodes et al. 2017; Kost et al. 2021; Erichsen et al. 2019; Satymov et al. 2022)

Figure 6: Suitability scores of wind energy in KSA (class: IEC I)

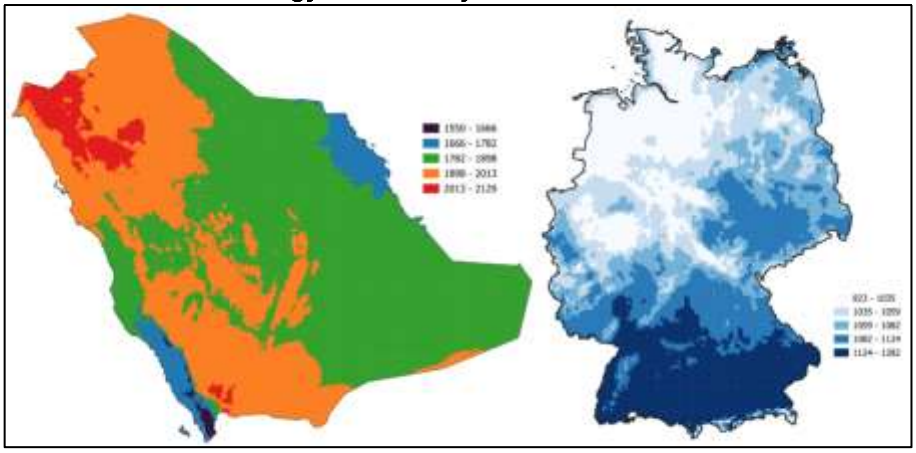


Source: Own analysis and visualization based on (GlobalWindAtlas 2023; Kontur 2023; OSM 2023; OpenTopography 2013; Mahdy et al. 2016)

2.3 Comparative advantage (KSA vs. Germany)

As shown in the previous section, the higher the capacity factor, the lower the LCOE as the produced energy increases while the employed equipment is still the same. Also, considering that the electricity cost is the decisive factor in the production cost of hydrogen, the direct production costs of hydrogen are dependent on the capacity factor. This is because the costs of the other production components (e.g. wind turbines, solar photovoltaic, electrolyser) are roughly constant everywhere. Considering this notion, we can compare between the potentials in both KSA and Germany. In terms of wind energy, we cannot recognize a clear comparative advantage. Only a few places (e.g. NEOM) have exceptionally very high CFs (up to 0.73) (Figure A10, Appendix 1). Contrariwise, KSA has a clear comparative advantage in terms of solar energy. The highest PVOUT in Germany is lower than the lowest one in KSA (Figure 7). In order to avoid the misinterpretation of the figures, we have to highlight that the area of Germany is one sixth the KSA's area.

Figure 7: The PVOUT of solar energy in Germany vs. KSA



Source: Own visualization based on (GlobalSolarAtlas 2023)

2.4 Land use

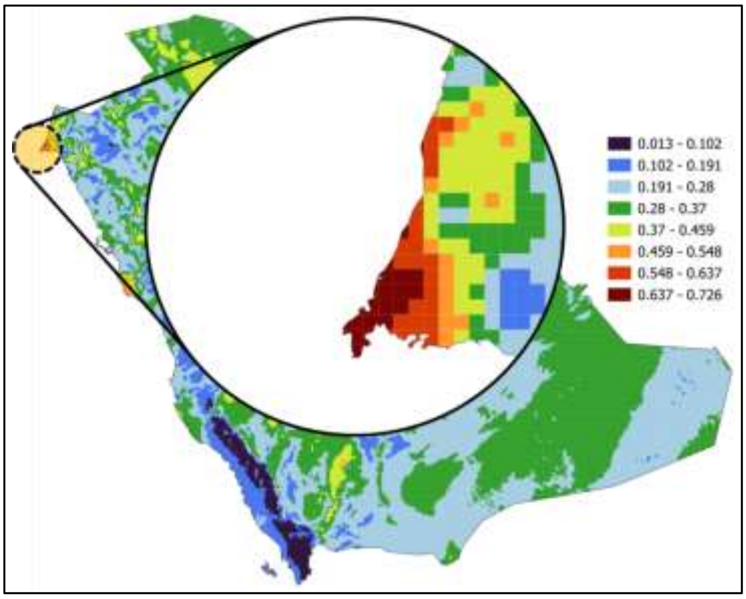
Land use is one of the main considerations while designing RE plants and supply chains. Not only photovoltaics need enough space to receive the solar energy (Layton 2008), wind parks is also associated with extensive land use due to the wake effect. After the wind stream passes through a wind turbine, it losses some energy and becomes more turbulent, which is called the wind turbine wake (González-Longatt et al. 2012). This wake effect prevails within a certain distance beyond the wind turbine, which is why there is usually an enough space between wind turbines to minimize the wake effect and maximize energy production in the wind farm (Asnaz et al. 2020). Hence, the alignment and configuration of wind turbines are critical for maximizing energy production and profits. There are already various models to define the suitable distances (Sawant et al. 2021; Stevens et al. 2016; Gupta 2016). This indicator is called "capacity density" and can be defined as the ratio between the nominal capacity and the area it occupies (MW/km^2). This implies that the land footprint of the project determines its capacity density. For example, the capacity density of a wind farm is the ratio between the total installed capacity and the RE farm area.

It is important to differentiate between two different indicators: capacity factor and capacity density. The first is concerned with the ratio between the amount of energy that can be generated at certain location and the rated capacity (CSS 2023). Therefore, the capacity factor directly impacts the economic performance of the project as locating the project in a good location implies higher energy production, and consequently higher revenues. For example, if we set the same wind turbine in two locations A and B, the energy generated by the wind turbine at location A will be double that produced at location B. On the other hand, the capacity density is usually an important theme if the project contains more than one wind turbine. In such case, the interaction of the wind turbine with other systems or wind turbine will determine its land use. We already mentioned the wake effect, which is mainly considered for techno-economic purposes. But that can also be relevant for social or environmental reasons. For example, if some regulations require minimum distance from buildings, landscapes, or forests, etc.

From the established wind farms that already exist all over the world, some empirical studies have defined the typical spacing and capacity densities in the different countries. The study of (Harrison-Atlas et al. 2021; Giani et al. 2020) has pointed out that the capacity density in KSA ranges between 4.9 and 7.9 MW/km^2, which are lower than the figure in Europe (higher than 11 MW/km^2) (Enevoldsen and Valentine 2016; Enevoldsen et al. 2019; Harrison-Atlas et al. 2021). As there is, so far, no competition over land in the investigated region (KSA), the capacity density is probably not that high. Nonetheless, competition over the areas with high RE potential could lead to higher capacity densities in the future.

In order to demonstrate the land use of wind energy in KSA, we provide a quantitative example from NEOM (Figure 8 and eq. 11 in Appendix III). The dark red blocks have the highest capacity factors (range between 0.637 and 0.726). Such exceptionally high CFs result in a very low LCOE (between 0.018 and 0.02 EUR/KWh). This area is also well located as it has access to the sea. Nonetheless, the geographical availability of these blocks is limited, approximately 340 km^2 (≈ half of Singapore's area). If we consider an average capacity density of 6.4 MW/km^2 in KSA, this area can then accommodate a capacity of roughly 2.2 GW, which can produce approximately 13 TWh/year. Using the generated electricity to produce hydrogen with the current electrolysis technologies can produce more than 250 kt H_2 per year. This number corresponds to half of the German steel sector's demand by 2050. Hence, despite the significance of the number, more production capacities will still be needed. Therefore, once the area is occupied by wind farms, the investments will have to go to the following favorable regions (light red → orange → yellow).

Figure 8: Capacity factors of wind resources in NEOM



Source: Own analysis and visualization based on (GlobalWindAtlas 2023)

3. Beyond production costs: impact of the other factors on the supply chain

3.1 Externalities

So far, the numbers have been focusing on the direct costs. Nonetheless, there are also other externalities that need to be taken into consideration. Wind and solar farms occupy large areas (Harrison-Atlas et al. 2022). Also, as the available capacities of unpopulated windy areas are getting exploited, the wind farms get more and more closer to the residential areas. Therefore, the challenge is not only related to land availability, but also the NIMBYism (NIMBY: Not in My Back Yard) (Bell et al. 2005). The existence of wind turbine can negatively impact the scenery and cause noise for the residence (Saunders 2020). In turn, this can reduce the value of the assets and real estate in the neighborhood (Hoffmann and Mier 2022). The study of (Jensen et al. 2014) estimates that the visual and noise pollutions can reduce the property value by 3% and (3%-7%), respectively.

That's why we can witness an increasing trend of social resistance regarding the development of RE projects in the residential areas. Either it results in noise, scenery distortion, loss of real estate's value or the need to compensate the locals, the total costs of RE production in the relevant area will increase. Herein, the spatial pattern of the population distribution has a major impact. Countries where the population spread over the territories will face higher levels of NIMBYism. The analyses of (Hoffmann and Mier 2022) estimates the damages could be between 293 and 1400 billion EUR in Germany by 2045. The exact impact seems controversial as the literature contains other higher and lower figures. However, there is no doubt that this impact is more prominent in the countries with limited land and higher population densities, such as Germany.

The population density and distribution in Germany and KSA are different (See Figure A11, Appendix I). The KSA territories are roughly half of the EU area and have less than half of the population in Germany (EU 2023). The population is concentrated in certain regions and cities and the rest of the country has very low population densities or even no inhabitants. For example, Al Rub' Al Khali (The empty quarter), located in the south and south east, has a massive area with roughly no population (650,000 km^2) (Albraheem and AlAwlaqi 2023). This area corresponds to the area of France, Belgium, and the Netherlands, combinedly, or roughly double the area of Germany. According to (Salam and Khan 2018), half of the solar radiation on this region can satisfy the global power demand. Hence, we can state that the importer does not only receive cheap energy, but also cheap land use (or cheaper externalities).

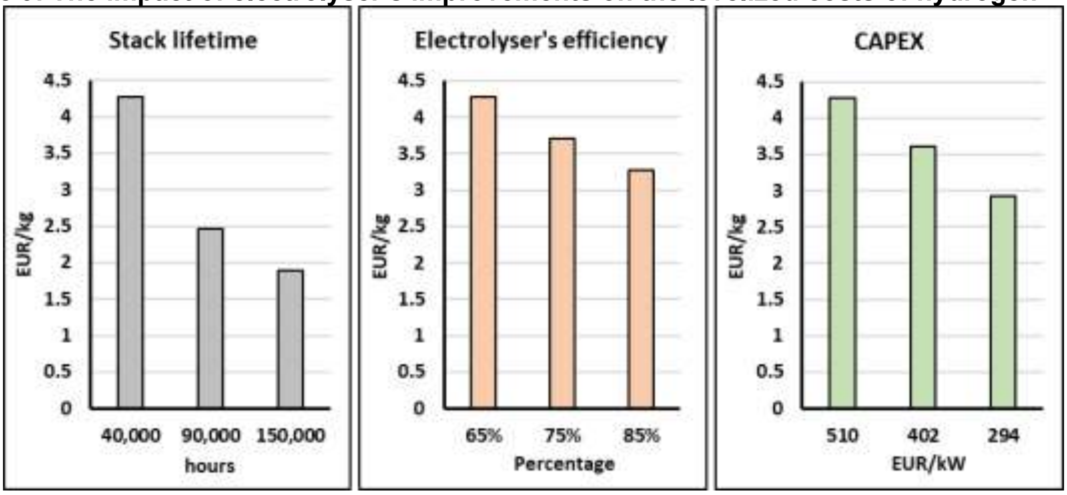
Nonetheless, having no population, infrastructure, road and power networks poses a major challenge (Qamar Energy 2018). For example, as discussed earlier while determining the suitability scores, wind and solar farms cannot be built too much close from the roads (500 m). Nonetheless, beyond this threshold, the nearness to the road is advantageous and gets higher suitability scores. The infrastructure systems (e.g. road networks) are usually built to provide the relevant services to a high number and wide range of beneficiaries, which make them sensible from an economic perspective. In the case of unpopulated areas, dedicated infrastructure systems would be needed in these regions, which maybe only used to service the wind and energy parks. Such circumstance implies that the ratio between the required investments and utilization can be too high.

It seems that there is a lack of studies on this region (e.g. the challenges that may be associated with the establishing the required infrastructure and networks). If the externalities are high, these areas can be a promising solution. Herein, the decision- and policymakers will have a trade-off between externalities and additional costs of the required infrastructure in these regions (which currently have low suitability scores, as shown in Figure 6).

3.2 Uncertainties and technology improvements

The numbers presented in section 2 are based on the techno-economic performance of the current technologies. As discussed earlier, wind and solar energies have witnessed costs reductions in the last decades due to the high installed cumulative capacity (S&P Global 2023). Contrariwise, the industrial deployment of electrolysers is still limited, which is why their TRL is moderate, and their costs are still high. Therefore, by comparing the expected cost reductions in the future, the costs of electrolysers will decrease more than wind turbines and solar photovoltaics. Such cost reduction has a crucial impact on the hydrogen production costs. As shown in Figure 9, the expected CAPEX reduction from 521 EUR/kWh to 294 EUR/kWh by 2050 will reduce the LCOH from 4.3 to 2.9 EUR/kg H_2.

Figure 9: The impact of electrolyser's improvements on the levelized costs of hydrogen



Source: Own analysis and visualization based on (GlobalWindAtlas 2023; Rhodes et al. 2017; Kost et al. 2021; Erichsen et al. 2019; Satymov et al. 2022; IRENA 2021b; Corbeau and Merz 2023)

The technology performance will also improve as the learning curve is developing. The electrolyser's efficiency is also expected to reach higher values (IRENA 2021b). Considering an efficiency of 75% and 85% will decrease the LCOH to be 3.7 and 3.3 EUR/kg H_2. There is also a lot of uncertainty regarding the costs and lifetime of the stacks now and in the future (Corbeau and Merz 2023). Some studies report lifetimes of up to 90,000 hrs (now) and 150,000 hours (in the future). Such performance improvement has a substantial impact on the costs. For example, considering lifetimes of 90,000 and 150,000 hours result in LCOH of 2.5 and 1.9 EUR/kg H_2, respectively. If all these techno-economic improvements are applied simultaneously (stack lifetime = 150,000 hr, electrolyser's efficiency = 85% and CAPEX = 294 EUR/kW), the LCOH decreases significantly to 1.18 EUR/kg H_2.

In our analysis, we also assume that the required electrolyser's capacity is equal to the installed wind and solar capacity. This implies that the electrolyser's capacity factor is very high at peak times and low the rest of the day. Similar to renewable energies' technologies, the capacity factor of the electrolyser is the ratio between the actual production to the maximum possible production or the ratio between the operating hours to the total number of hours in one year. Hence, lower capacity factors imply lower utilization of the capital, and consequently higher levelized costs (IRENA 2018). This can be tackled through system balancing, for example by integrating power storage (e.g. batteries) and oversizing the capacity of solar and wind farms (Krohn et al. 2009; Ali Khan et al. 2021). While this may entail additional costs, it also leads to higher output.

Although these changes can improve the economic performance, the capacity factors of wind and solar energy are still very impactful on the levelized costs. Nonetheless, efficient operations are needed to minimize the costs as much as possible. In order to carry out further optimization, other input data will need to be integrated (e.g. the daily profiles of wind and solar energies), which can be an extension of this study. Herein, we can deduce some trade-offs along the system: (1) the electrolyser's capacity factor and electricity costs, (2) electrolyser's capacity factor, PV/wind farm capacity factor and oversizing factor (Ali Khan et al. 2021).

3.3 Transportation

The proximity to the consumption point can be a critical factor as hydrogen transportation can impact the prospective supply chain significantly. For example, the transportation costs of hydrogen can be as expensive as the production costs (Heinemann et al. 2022b; Heinemann et al. 2022a). Herein, there are multitude of options as there are different hydrogen carriers (e.g. liquid hydrogen, ammonia & LCOH) as well as various transportation modes (Preuster et al. 2017). The exporter would be open to any configuration as long as it will reach the consumer as hydrogen or hydrogen derivative at the lowest cost. As such supply chain does not exist yet, there is no real data to carry out empirical analyses.

Herein, the assumptions play a major role and can impact the outcomes significantly. Also, each case has to be investigated individually. According to (IEA 2019), shipping is more favorable for distances above 1500 km and pipeline is more cost-efficient below this value. As Europe is the targeted market in our case, the distance is higher than this threshold, making shipping the most efficient mode of transportation.

Since the solar and wind farms may not be always located close to the export harbor, the produced energy has to be firstly transported domestically. In this regard, there have been ongoing discussions regarding the transportation mode after power production from the wind or solar farms, i.e. is it better to transport electricity and then produce hydrogen or should we produce hydrogen directly and then transport it by pipeline.

It is widely agreed upon that electrification (i.e. direct electricity consumption) is the most preferable and efficient pathway due to the energy losses associated with transformation and transportation. In certain cases, it may make sense to compare batteries and hydrogen regarding their ability to store energy, which is not the case while using hydrogen as a feedstock. As a rule of thumb, pipelines are generally cheaper than power cable to transport the same amount of energy bounded in hydrogen (APGA 2022; GPA 2022). The economies of scale make the specific transportation costs of both pipeline and powerline cheaper (see Figure A12, Appendix I). However, at the same (equivalent) flow rate, pipelines are much cheaper than power cable, especially at small flow rates. This can be mainly attributed to the construction and maintenance costs, land use and energy losses.

Overseas transportation

Overseas transportation also has an impact on the total costs. Once the hydrogen reaches the sea, we need to determine the suitable hydrogen carriers for shipping. There are different options (e.g. liquid hydrogen, ammonia and Liquid Organic Hydrogen Carrier (LOHC)), each of which has its own advantages and disadvantages (Weichenhain et al. 2021). Ammonia and LOHC shipping (around 0.2 EUR/kg H_2) are cheaper than hydrogen shipping (around 1 EUR/kg H_2) (Figure A13, Appendix I). Nonetheless, we also have to consider the conversion and reconversion costs. Although these processes are expensive, it could be cheaper if we consider hydrogen shipping within the same system boundaries (Collis and Schomäcker 2022). Table A2 in Appendix II shows the CAPEX and OPEX of the relevant processes and operations, based on (Vos et al. 2020). If we assume a capacity factor of 1 and electricity costs of 0.03 EUR/kWh, the levelized costs of conversion to ammonia and ammonia cracking will be 0.5 and 0.25 EUR/kg H_2, respectively. As the hydrogen shipping also needs liquefaction and regasification, we can confidently conclude that ammonia shipping is more economic. Considering that ammonia shipping is already an established industrial practice with a high TRL can also reinforce this conclusion.

Due to the low shipping costs of ammonia, the consumer’s location should not be a significant barrier. For example, while the transportation distance from KSA to Tokyo is roughly double the distance to Hamburg (Figure A14), the transportation cost is roughly 0.41 instead of 0.28 EUR/kg H_2. In order to reduce the transportation costs, both domestically and overseas, it may make sense to have the production facilities and exporting harbors in the west of KSA. As depicted previously in Figure 2, there are already various ports on the western coast, which can be developed further to be green hydrogen hubs. Although the Eastern ports may be more developed due to the existing oil and gas infrastructure, saving the transportation costs may still have higher impacts on the economic performance. Additionally, the higher availability of RE resources in the western part will also lead to higher cost efficiencies.

4. Exporter vs. importer: contrasting the perspectives of Saudi Arabia and Germany

As the RE availability varies widely, it is important to quantify these resources and pinpoint the most suitable locations. This will help in showcasing the array of options available to the prospective exporters and understand the inherent trade-offs involved. Also, as hydrogen is going to reshape the global energy market and its dynamics, the relevant policies and geopolitical aspects should be considered (de Blasio and Pflugmann 2021). This section provides additional reflections on what do these quantitative analyses imply for the prospective supply chain and trading route. In this section, we discuss these facets through four pivotal questions:

- Where to produce?
- Which products to produce?
- How competitive is this value chain compared to other routes?
- What are the geopolitical factors and policy implications?

4.1 Where to produce? Location strategies and trade-offs

RE availability and land suitability vary significantly, necessitating optimization of infrastructure and cost reduction across dimensions like location, time, and scale. The decision makers encounter several trade-offs that will shape the prospective supply chain. Solar energy exhibits widespread availability throughout KSA with minor variances, whereas wind energy is concentrated in specific regions, requiring careful site selection to cut production costs. Also, if there is competition over a location, the priority should be given to wind farms due to the limited availability compared with solar energy. NEOM is obviously the most suitable location for wind parks and green hydrogen production. Nonetheless, once the available space is exploited, other locations must be investigated. In terms of competitiveness, the nominal costs and availability of wind energy in KSA are close to Germany, except in certain locations (e.g. NEOM). However, if externalities, area, and land-use are taken into consideration, the cost-efficiency and availability of onshore wind energy in KSA are higher. In terms of solar energy, all locations in KSA are superior as the lowest capacity factor of solar energy there is higher than the highest in Germany.

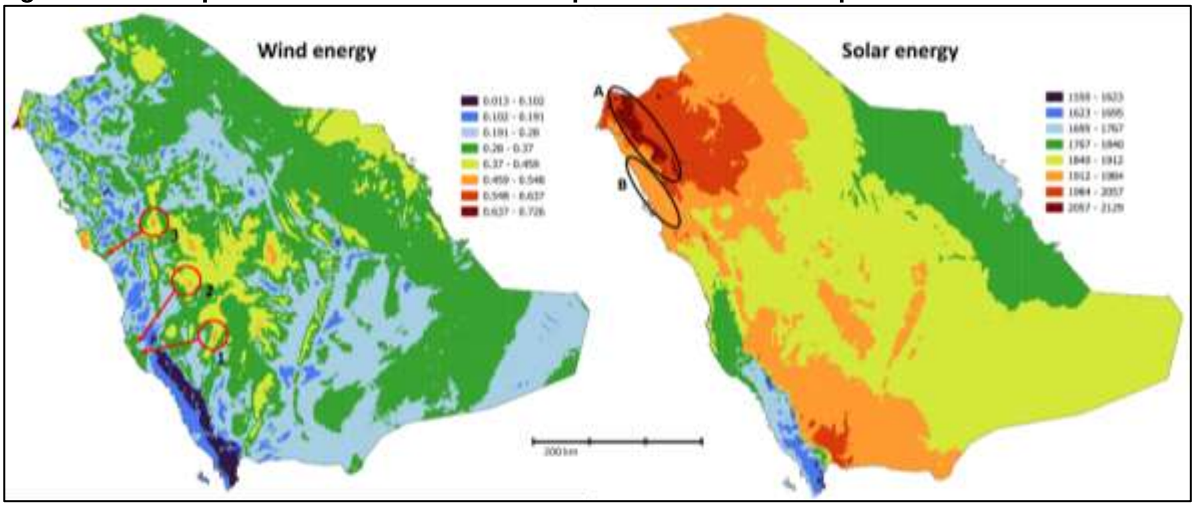
Given the high potentials of onshore wind and solar energies in KSA, we may ask if utilizing offshore wind energy makes sense in KSA. Offshore wind farms are often established to overcome limitations such as resource scarcity or land availability (Esteban et al. 2011), notably observed in Europe where approximately half of the global offshore wind capacity is concentrated (WFO 2023). However, offshore wind systems are inherently more complex and expensive compared to onshore wind and photovoltaics, with specific costs ranging between 2 to 5 million EUR/MW (Kaldellis et al. 2016; Voormolen et al. 2016). Moreover, offshore wind energy is associated with techno-economic risks and uncertain learning curves, as recent years have seen cost increases due to factors like longer distances from shore, greater depths, harsher environments, and environmental impacts (Voormolen et al. 2016; Lloret et al. 2022). Consequently, recent studies approach offshore wind energy with a recognition of its considerable uncertainty, challenging prior optimistic cost estimations (Sykes et al. 2023; Beiter et al. 2023; Schwanitz and Wierling 2016).

While some studies showcased the potential of offshore wind energy in KSA (Mahdy et al. 2016; Sundaram et al. 2020; Waheeb et al. 2023; Elzemeity et al. 2021), it may not be strategically prudent to prioritize its consideration in the short to medium term. The context is different than Europe where the land availability and externalities impact the technological choices significantly. Given the huge area that KSA is endowed, it makes more sense to depend more on onshore wind. Offshore wind does not incur any advantages, at least in the time being, due to the availability of land and low externalities in KSA.

When it comes to the placement of solar and onshore wind farms, it is undoubtedly more advantageous to locate them near the coast to minimize the costs. Nonetheless, once the advantageous areas there are exploited, a trade-off emerges between transportation and production costs, aiming to minimize the combined expenses. For example, some advantageous regions are far away from the sea, which implies additional transportation costs. Contrariwise, transportation is not required for less-advantageous areas close to the sea. Here, the decisive factor is the difference in capacity factor (CF). If the CF difference is high enough, transportation makes sense and vice versa.

For example, let's consider whether it's preferable to produce wind power and hydrogen in the orange blocks (average CF = 0.51) versus green blocks close to the sea (average CF = 0.325) (Figure 10). The first option results in a lower LCOE of 0.026 EUR/kWh compared to 0.04 EUR/kWh. For hydrogen production, it implies a LCOH of 4.57 EUR/kg, instead of 5.26 EUR/kg. Factoring in pipeline transportation over this distance (approximately 200 km) would add approximately 0.1 EUR/kg H_2. Therefore, prioritizing the orange blocks (1, 2 and 3) makes economic sense. As these calculations follow the same approach presented earlier, this relative difference can be even higher in the future. The same concept can also be applied on solar energy (locations A and B). Nonetheless, as mentioned, the variance of solar energy is not significant in the western part of KSA. This may imply that producing close to the coast may have lower total costs.

Figure 10: Examples of the trade-off between production and transportation costs



Source: Own analysis and visualization based on (GlobalWindAtlas 2023; GlobalSolarAtlas 2023)

4.2 Which products? Demand and uncertainties

Based on the preceding discussion, producing and exporting ammonia is more favorable than hydrogen. In such case, ammonia cracking is not needed and the conversion process is a key part of the production process and not only a transportation phase. Additionally, this scenario implies that green ammonia can be used directly with the same downstream processes (i.e. no need to change or retrofit the relevant technologies of subsequent phases, which is mandatory in several cases such as using hydrogen in steel production). It can also be a ramp-up route in the short-term until other segments are technologically and economically ready to consume green hydrogen. Therefore, from a hydrogen producer's perspective, the industrial feedstock (especially green ammonia) can be considered as the most-efficient pathway and the safest market segment (Weichenhain et al. 2021).

There is already a demand for industrial feedstock in Europe this decade (starting from 8 Mt H_2) while the hydrogen demand of mobility and heat & power sectors starts to be more obvious from 2030 on (Figure A15, Appendix I). Eventually, the demand of industrial feedstock will be approximately 16 Mt H_2. However, it should be noted that the analyses of (IRENA 2021a) envision a different H_2 demand growth. Also, the study of (Andreola et al. 2021) reports approximately half of this figure and classifies them into different industries. They envisage that the demand will be dominated by refineries and ammonia until 2030. From 2040 on, the demand will be mainly from steel, ammonia, and chemical recycling. In terms of the ammonia demand, there are two locations with 12.2 TWh (approximately 2.4 million tons ammonia). The demand of iron and steel sector is concentrated at the locations of the primary steel producers, such as ThyssenKrupp in Ruhrgebiet and Salzgitter in Lower Saxony. Combinedly, this sector will need approximately 18.8 TWh, which correspond to more than half million tons hydrogen (see also Figure A16 in Appendix I which shows the demand of main industrial consumers in Germany by 2050).

4.3 How competitive is this value chain compared to other routes?

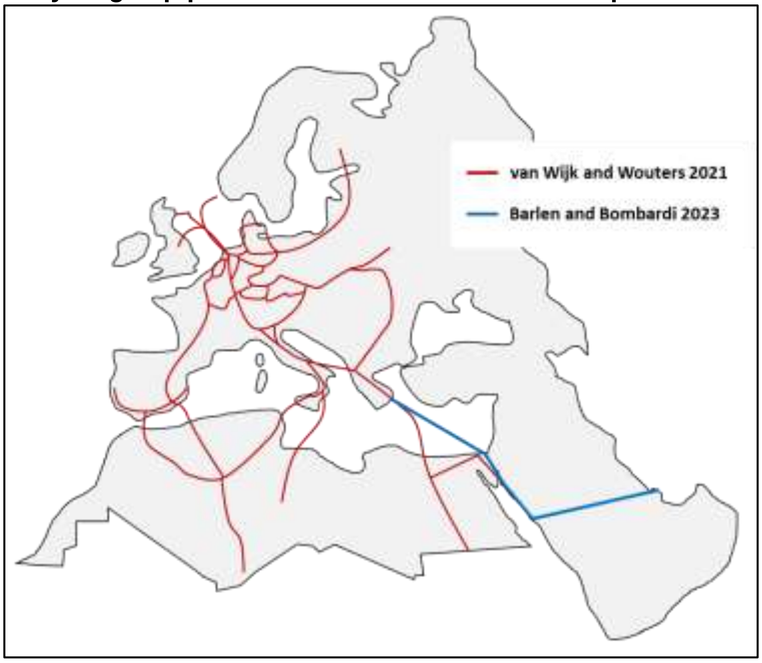
This question is closely intertwined with the preceding one. Although green ammonia production and shipping can be economically justifiable, it will not be able to provide cheap hydrogen for other market segments (e.g. steel, heating, and mobility). Transformation to ammonia, shipping and ammonia cracking can be considered additional burdens to the total hydrogen costs. As indicated in the preceding section, these additional operations will cost more than 1 EUR/kg H_2. Therefore, with conversion and transportation factored in and utilizing current technologies, the total costs reach 5.31 EUR/kg H_2 (CF in NEOM = 0.726). The total costs can also increase if locations with lower capacity factors are selected. By including the potential techno-economic developments outlined in 3.2, the total costs are anticipated to decrease to 2.23 EUR/kg H_2. Although these values are higher than the average price of grey hydrogen in Germany before the war in Ukraine (1–2 EUR/kg H_2) (Frontier Economics 2021; Edison 2021), grey hydrogen will not be able to compete sooner or later as the carbon prices are increasing over time. The real competition will emerge from other exporters of green hydrogen.

The commodity price at the consumption site should be the main criterion to assess the potentials of prospective hydrogen routes or supply chains. Hence, if other suppliers succeeded to eliminate the cost of conversion and ammonia cracking from their operations, they will be able to deliver the hydrogen in more affordable prices. Screening the potential competitors, the North African countries have high potentials to provide hydrogen to Europe at competitive prices (Barnard 2022). Countries such as Morocco, Algeria, Tunisia, and Egypt have immense amounts of land as well as abundant RE resources. Therefore, the production costs would be roughly the same in both regions. Nonetheless, the comparative advantage of North Africa would be the cheap transportation costs via pipelines as the conversion and shipping costs will are eliminated. On the other hand, the hydrogen exports from North and South Americas to Europe may not present additional advantages compared to KSA due to the long distances.

As shown in Figure 11, there are potential linkages of hydrogen pipelines between the EU and Africa. Parts of this network will be established via retrofitting the existing natural gas network that links Alegria, Morocco and Tunisia with Spain and Italy. That may imply higher competitive advantages for the potential exporters from North Africa. Since those countries also have abundant renewable resources, the cheap transportation costs may play a decisive role. As this network is unlikely to be realized within this decade, shipping may be a convenient transportation mode in this transition period. Nonetheless, pipelines are anticipated to emerge as a convenient and efficient mode of transportation for the European market. Shipping may also continue to be suitable for other importers such as Japan. Producing and exporting ammonia (to be used as ammonia) maybe risky, but still feasible (especially with high oil prices). However, converting the hydrogen to ammonia and then cracking ammonia to generate hydrogen may not make a lot of sense.

Some studies (e.g. (Barlen and Bombardi 2023)) provide conceptual designs for a potential pipeline connection between KSA and Europe (blue polyline, Figure 11). These studies usually focus on the construction costs of the pipeline. However, there are several implicit challenges such as the legal and regulatory complexities if the pipeline is going to pass through several countries. Additionally, even with the optimistic perspective of (Barlen and Bombardi 2023), the transportation cost is expected to be 1.2 EUR/kg H_2, which may represent a crucial share of the total costs in the future. Hence, the North African countries would have more advantageous situation due to their lower transportation costs by pipeline. Therefore, pursuing a pipeline connection alone can entail numerous uncertainties. Thus, joining the endeavors of the African countries can reduce both expenses and risks. If the connection to the pipeline is not feasible, a direct attention towards ammonia may present a more secure strategy. Furthermore, there are other hydrogen-based value chains that can be promoted, which can eliminate the comparative advantage regarding location and enhance the value added in KSA. For example, besides ammonia, producing direct reduced iron can be a good business model due to its low transportation costs compared to hydrogen.

Figure 11: Potential hydrogen pipeline connections between Europe and Africa



Source: Sketched based on (van Wijk and Wouters 2021; Barlen and Bombardi 2023)

4.4 What are the geopolitical factors and policy implications?

The exporters and importers possess different motives and objectives, as well as facing distinct risks and uncertainties. Hence, it is essential to consider the perspectives of both KSA and Germany. The momentum behind hydrogen economy coincides with both (1) the availability of solar and wind resources in the MENA region and (2) the ambitions of the MENA countries to diversify and develop their economies or maintain their geopolitical influence (Koch 2022).

During this early stage of market and technology development, the hydrogen producer may encounter a strategic question: what if hydrogen is a hype? Hydrogen is, and will be competing, with other technologies. The outcomes of some battles are quite expected or can be expected, while the others are unknown because it depends on several factors (e.g. market development, the improvements of technology performance, etc.). For example, the recent study of (Schreyer et al. 2024) anticipates that the hydrogen share in the EU energy share may range between 10% and 25% by 2050, highlighting significant associated uncertainties.

While the costs of electrolysis are expected to decrease, it is probably controversial how much this decrease will be. Comparing the technology with the production and installation conditions of the other relevant technologies that emerged in the last decades, we can expect that the electrolyser is going to behave similar to onshore wind turbines and solar PVs. Conversely, the retreats of offshore wind energy are less expected. Therefore, the stakeholders strongly believe that the technology will develop a learning curve and costs will decrease gradually. For example, according to (IRENA 2021b), the production costs of green hydrogen are going to decrease by 60% by 2030 as a result of higher TRLs and economies of scale. Some studies expect that the prices will continue to decrease until 2050, reaching one-fourth of their current value (Anouti et al. 2020). Hence, the critical question is: whom or which stakeholder is going to pay for the cost of learning?

Here, the producers encounter a dilemma. Although the first movers benefit from the acquired know-how, the knowledge and experiences gathered may not justify the high investments, especially if preventing all spillovers is roughly impossible. Additionally, the risks and uncertainties are very high at such first stages of technology development. Therefore, without governmental investments or support, building such industrial-scale plants can be seen very risky and an irrational decision from the private sector's perspective. Even from the state's perspective, the first-mover strategy can still be risky as the public money can be dissipated if other regions succeeded to reap the benefits of the spillovers and lower costs. Hence, the decisive criterion is how quick the first mover can develop a cluster and reap the vantages of the early know-how and economies of scale. Also, presenting the respective country as a committed hydrogen provider is also an important factor in developing a hydrogen cluster. Again, we have another trade-off; the burden of expensive technology costs and learning expenses versus positioning the country as a reliable and ambitious supplier.

Although the uncertainties and risks decrease with time, they will continue to exist in the short and medium terms. Also, the required momentum and scale cannot be realized with the conventional business models. Hence, the role of state is indispensable, and governmental investments may be mandatory. There are clear signs that KSA is a first mover, but with cautious steps. With the green ammonia project in NEOM, there is a clear sign of commitment. NEOM Green Hydrogen Company (NGHC), which is a joint venture of NEOM, ACWA Power and Air Products, has recently announced a final investment decision of more than 8 Billion USD (NEOM 2023). With a production of 1.2 million ton ammonia, we can estimate a levelized cost of more than 1000 EUR/ton ammonia. NGHC has also concluded an offtake agreement for 30 years with Air Products (Martin 2023). We can also notice a continuous call for more agreements with potential importers.

In terms of the German perspective, it can be understood within the EU sphere. The EU as well as Germany aim at a competitive, sustainable and secure energy system (Birchfield and Duffield 2011). Although the theme of sustainability had the highest priority in the EU agenda during the last decade, the need for energy security has been augmented after the war in Ukraine. Hence, the EU and German policies aim at preventing comparable market shocks and ensuring stable energy supplies via diversification. Germany is actively engaging in shaping the hydrogen supply chain, not merely as a technology provider but also as a proactive participant. Recognizing that early adopters will shape the future rules, Germany is eager to position itself accordingly. While the endowment of fossil resources has shaped their global supply chains in certain configuration, the distribution of RE resources will allow several countries to be net exporters. Thus, diversification can be more conceivable in hydrogen supply chains, which align with the German and European endeavors.

Germany is projected to be a net hydrogen importer (Wietschel et al. 2020). While between 90 and 110 TWh hydrogen demand will be needed by 2030, only 14 TWh are expected to be produced domestically (McWilliams and Zachmann 2023). Although some EU countries (e.g. Portugal, Spain, and Norway) are going to be net exporters (green and blue hydrogen), the EU is expected to be a net importer. According the REPowerEU plans, EU shall import as much as its production by 2030 (10 Mt each) (Ansari et al. 2022). In terms of hydrogen production capacities, 118 GW should be installed by 2030, of which more than 60% shall be in Spain. Thus, Germany will not be able to satisfy its demand completely within the EU domain. Herein, as discussed earlier, there are countries outside the EU that may emerge as potential exporters.

In this regard, the importing country (e.g. Germany) may encounter comparable risks as the exporter. Various geopolitical, economic and social factors can serve as indicators of the feasibility and reliability of potential trading routes (Sprenger et al. 2023). At present, the economic aspects can be considered the most influential in terms of the impact on the potential supply chain. Despite KSA having lower production costs, getting involved in a long-term purchase agreement too early can result in paying higher prices for hydrogen than what might be available in the future. Consequently, there are evident signs of reluctance from Europe to engage in such agreements prematurely, indicating a wager on lower prices. This is indeed the major dilemma of the green hydrogen supply chain. Developing technology requires time and investment to attain higher maturity levels, but it is unclear who is going to pay. Herein, mitigating and distributing investment risks can prove to be an effective strategy to assist in this regard (Janzow et al. 2022). H2Global, EU Hydrogen bank, Carbon Contracts for Differences, EU innovation fund projects, Projects of Common Interest (PCI), etc. represent promising approaches, but within the EU sphere (EC 2022; Mezősi et al. 2023; EIB 2023). Cross-border collaborations outside the EU have mainly taken a diplomatic approach so far. Hence, there is a pressing need for analogous concepts to address potential hydrogen suppliers beyond the EU borders. If Germany is to source a crucial part of its energy consumption from countries outside the EU, more commitment should be demonstrated. Hence, the talks with the relevant exporters should be materialized in a faster pace, as it has equal importance for both parties, if not higher for Germany.

5. Conclusions

Green hydrogen emerges as a promising solution to the intermittency of renewable energy resources, offering storage and transport capabilities essential for a sustainable energy future. However, establishing a viable green hydrogen supply chain poses multifaceted challenges, including high conversion costs and logistical complexities. Given the substantial gap between regional supply and projected demand, international collaboration is essential to bridge this disparity. Germany's proactive hydrogen diplomacy exemplifies the strategic importance of securing reliable supply chains, with a potential trading route emerging between Germany and the Gulf region. However, it is crucial to consider the cost dynamics of the entire supply chain, encompassing production, conversion, and transportation expenses, to derive effective strategies and policies.

The analyses highlight Saudi Arabia's comparative advantage in green hydrogen production, driven by its abundant renewable energy resources and land availability. The quantitative assessments compare the levelized costs of wind and solar energies, indicating a lower variance in solar energy costs compared to wind. This suggests that solar parks can be constructed more flexibly, whereas onshore wind farm locations require careful selection. For instance, using the highest wind CF (0.726) results in LCOH of 4.28 EUR/kg H_2, while a lower CF (0.4) increases the LCOH to 4.91 EUR/kg H_2. In terms of location, the placement of solar and wind farms near the coast minimizes costs. But as the prime areas are utilized, a trade-off arises between transportation and production costs. Uncertainties in future cost reductions and technological improvements in the electrolysis technology are also explored. Some studies predict substantial drops in electrolyser capital costs (e.g. (Reksten et al. 2022)), plummeting from 521 EUR/kWh to 294 EUR/kWh by 2050. Such decrease is set to lower the levelized cost of hydrogen from 4.3 to 2.9 EUR/kg H_2. Technological advancements, including increased electrolyser efficiency and longer stack lifetimes, could further decrease the LCOH to as low as 1.18 EUR/kg H_2, highlighting the potential for substantial cost reductions in green hydrogen production.

Hence, considering uncertainties, externalities, technological advancements, and transportation is of importance to assess the risks and economic viability of the potential value chain. Additionally, location strategies, product selection, competitiveness, and geopolitical factors all play significant roles in shaping the green hydrogen market. For potential exporters like Saudi Arabia, addressing these strategic aspects is essential to capitalize on their renewable energy potentials and establish themselves as key players. For example, the paper demonstrates that focusing on ammonia production and exploring other hydrogen-based value chains (e.g. direct reduced iron) can offer a more secure strategy via negating the location-based competitive edge of potential competitors (North African countries). The discussion also delves into the perspectives of both exporter and importer, revealing key considerations for each party and suggesting appropriate strategies to mitigate risks and uncertainties.

References

Albraheem, Lamya; AlAwlaqi, Lama (2023): Geospatial analysis of wind energy plant in Saudi Arabia using a GIS-AHP technique. In *Energy Reports* 9, pp. 5878–5898. DOI: 10.1016/j.egyr.2023.05.032.

Ali, Amjad (2023): Transforming Saudi Arabia's Energy Landscape towards a Sustainable Future: Progress of Solar Photovoltaic Energy Deployment. In *Sustainability* 15 (10), p. 8420. DOI: 10.3390/su15108420.

Ali Khan, Muhammad Haider; Daiyan, Rahman; Han, Zhaojun; Hablutzel, Martin; Haque, Nawshad; Amal, Rose; MacGill, Iain (2021): Designing optimal integrated electricity supply configurations for renewable hydrogen generation in Australia. In *iScience* 24 (6), p. 102539. DOI: 10.1016/j.isci.2021.102539.

Alkousaa, Riham (2024): Germany earmarks up to $3.8 bln for future green hydrogen imports. Available online at https://www.reuters.com/sustainability/sustainable-finance-reporting/germany-earmarks-up-38-bln-future-green-hydrogen-imports-2024-02-20/, checked on 2/24/2024.

Andersson, Joakim; Grönkvist, Stefan (2019): Large-scale storage of hydrogen. In *International Journal of Hydrogen Energy* 44 (23), pp. 11901–11919. DOI: 10.1016/j.ijhydene.2019.03.063.

Andreola, Stefano; Menos-Aikateriniadis, Christoforos; Paxton, Angus; Preißler, Hannes; Miehling, Hannes; Rehn, Markus et al. (2021): No-regret hydrogen - Charting early steps for H2 infrastructure in Europe. Agora Energiewende. Available online at https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_02_EU_H2Grid/A-EW_203_No-regret-hydrogen_WEB.pdf, checked on 11/15/2023.

Anouti, Yahya; Elborai, Shihab; Kombargi, Raed; Hage, Ramzi (2020): The dawn of hydrogen - Maintaining the GCC's edge in a decarbonized world. Available online at https://www.strategyand.pwc.com/m1/en/reports/2020/the-dawn-of-green-hydrogen/the-dawn-of-green-hydrogen.pdf, checked on 12/12/2023.

Ansari, Dawud; Grinschgl, Julian; Pepe, Jacopo Maria (2022): Electrolysers for the hydrogen revolution.

APGA (2022): Pipelines vs Powerlines: a summary - Least-cost energy transport and storage in a net zero future. The Australian Pipelines and Gas Association Ltd (APGA). Available online at https://www.apga.org.au/sites/default/files/uploaded-content/field_f_content_file/pipelines_vs_powerlines_-_a_summary.pdf, checked on 11/27/2023.

Asnaz, Melike Sultan Karasu; Yuksel, Bedri; Ergun, Kadriye (2020): Optimal Siting of Wind Turbines in a Wind Farm. In J. A. Tenreiro Machado, Necati Özdemir, Dumitru Baleanu (Eds.): Mathematical Modelling and Optimization of Engineering Problems, vol. 30. Cham: Springer International Publishing (Nonlinear Systems and Complexity), pp. 115–137.

Barlen, Helge; Bombardi, Andrea (2023): Hydrogen pipeline from Gulf to Europe: use case and feasibility considerations - AFRY and RINA joint discussion paper. Available online at 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, checked on 1/14/2024.

Barnard, Michael (2022): Assessing EU plans to import hydrogen from North Africa: The cases of Morocco, Algeria and Egypt. Available online at https://www.tni.org/en/publication/assessing-eu-plans-to-import-hydrogen-from-north-africa#:~:text=This%20report%20shows%20the%20EU's,needs%20and%20local%20climate%20targets., checked on 1/15/2024.

Beiter, Philipp; Mai, Trieu; Mowers, Matthew; Bistline, John (2023): Expanded modelling scenarios to understand the role of offshore wind in decarbonizing the United States. In *Nat Energy* 8 (11), pp. 1240–1249. DOI: 10.1038/s41560-023-01364-y.

Bell, Derek; Gray, Tim; Haggett, Claire (2005): The 'Social Gap' in Wind Farm Siting Decisions: Explanations and Policy Responses. In *Environmental Politics* 14 (4), pp. 460–477. DOI: 10.1080/09644010500175833.

Betak, J.; Suri, M.; Cebecauer, T.; Skoczek, A. (2012): Solar Resource and Photovoltaic Electricity Potential in EU-MENA Region. 4 pages / 27th European Photovoltaic Solar Energy Conference and Exhibition; 4623-4626. DOI: 10.4229/27thEUPVSEC2012-6CV.3.51.

Birchfield, Vicki L.; Duffield, John S. (2011): Toward a Common European Union Energy Policy. New York: Palgrave Macmillan US.

BMWi (2020): The National Hydrogen Strategy. The Federal Ministry for Economic Affairs and Energy.

Bolson, Natanael; Prieto, Pedro; Patzek, Tadeusz (2022): Capacity factors for electrical power generation from renewable and nonrenewable sources. In *Proceedings of the National Academy of Sciences of the United States of America* 119 (52), e2205429119. DOI: 10.1073/pnas.2205429119.

Collis, Jason; Schomäcker, Reinhard (2022): Determining the Production and Transport Cost for H2 on a Global Scale. In *Front. Energy Res.* 10, Article 909298. DOI: 10.3389/fenrg.2022.909298.

Corbeau, Anne-Sophie; Merz, Ann-Kathrin (2023): Demystifying Electrolyzer Production Costs. Available online at https://www.energypolicy.columbia.edu/demystifying-electrolyzer-production-costs/, checked on 12/5/2023.

CSS (2023): Fact sheet: wind enery. Center for sustainable systems - University of Michigan. Available online at https://css.umich.edu/sites/default/files/2023-10/Wind_CSS07-09.pdf, checked on 12/12/2023.

de Blasio, Nicola; Pflugmann, Fridolin (2021): The geopolitics of renewable hydrogen. Available online at https://nrs.harvard.edu/URN-3:HUL.INSTREPOS:37372506, checked on 1/26/2024.

DFD; DFR (2022): Hydrogen - from hype to reality. Dubai Future Foundation; Dubai Future Research. Available online at https://www.dubaifuture.ae/wp-content/uploads/2021/10/Hydrogen-From-Hype-to-Reality-EN-v1.0.pdf, checked on 10/10/2023.

DFF; DFR (2022): Hydrogen - From hype to reality. Dubai Future Foundation (DFF); Dubai Future Research (DFR). Available online at https://www.dubaifuture.ae/wp-content/uploads/2021/10/Hydrogen-From-Hype-to-Reality-EN-v1.0.pdf, checked on 1/14/2024.

EC (2022): Innovation Fund - Best practices from previous Calls for Proposals: First call for large-scale projects and first call for small-scale projects launched in 2020. The European Commission. Available online at https://climate.ec.europa.eu/system/files/2022-01/policy_innovation-fund_best_practice_en_0.pdf, checked on 1/14/2024.

Edison (2021): Finding the sea of green – The opportunity and options for shipping green H2. Available online at https://www.edisongroup.com/thematic/finding-the-sea-of-green-the-opportunity-and-options-for-shipping-green-h2/, checked on 3/9/2024.

EIB (2023): Cross-border infrastructure projects: The European Investment Bank's role in cross-border infrastructure projects. The European Investment Bank (EIB). Available online at https://www.eib.org/attachments/lucalli/20230107_cross_border_infrastructure_projects_en.pdf, checked on 1/14/2024.

Elzemeity, Iman; Elsayeed, Ibrahim; Elzemeity, Asmaa (2021): Feasibility study of an Offshore Wind Farm with the Egyptian-Saudi Arabia HVDC link. In : 2021 6th International Conference on Renewable Energy: Generation and Applications (ICREGA). 2021 6th International Conference on Renewable Energy: Generation and Applications (ICREGA). Al Ain, United Arab Emirates, 2/2/2021 - 2/4/2021: IEEE, pp. 168–172.

Enevoldsen, Peter; Permien, Finn-Hendrik; Bakhtaoui, Ines; Krauland, Anna-Katharina von; Jacobson, Mark Z.; Xydis, George et al. (2019): How much wind power potential does europe have? Examining european wind power potential with an enhanced socio-technical atlas. In *Energy Policy* 132, pp. 1092–1100. DOI: 10.1016/j.enpol.2019.06.064.

Enevoldsen, Peter; Valentine, Scott Victor (2016): Do onshore and offshore wind farm development patterns differ? In *Energy for Sustainable Development* 35, pp. 41–51. DOI: 10.1016/j.esd.2016.10.002.

Erichsen, Gerrit; Ball, Christopher; Kather, Alfons; Kuckshinrichs, Wilhelm (2019): VEREKON Cost Parameters for 2050 in its Energy System Model. With assistance of TUHH Universitätsbibliothek.

Esteban, M. Dolores; Diez, J. Javier; López, Jose S.; Negro, Vicente (2011): Why offshore wind energy? In *Renewable Energy* 36 (2), pp. 444–450. DOI: 10.1016/j.renene.2010.07.009.

EU (2023): Facts and figures on life in the European Union. Available online at https://european-union.europa.eu/principles-countries-history/key-facts-and-figures/life-eu_en, checked on 11/27/2023.

Frontier Economics (2021): RED II green power criteria - Impact on costs and availability of green hydrogen in Germany: Short study for RWE AG. Available online at https://www.efuel-alliance.eu/fileadmin/Downloads/red-ii-green-analysis.pdf, checked on 3/9/2024.

Gharaibeh, Anne A.; Al-Shboul, Deema A.; Al-Rawabdeh, Abdulla M.; Jaradat, Rasheed A. (2021): Establishing Regional Power Sustainability and Feasibility Using Wind Farm Land-Use Optimization. In *Land* 10 (5), p. 442. DOI: 10.3390/land10050442.

Giani, Paolo; Tagle, Felipe; Genton, Marc G.; Castruccio, Stefano; Crippa, Paola (2020): Closing the gap between wind energy targets and implementation for emerging countries. In *Applied Energy* 269, p. 115085. DOI: 10.1016/j.apenergy.2020.115085.

GlobalSolarAtlas (2023): Introduction: The Global Solar Atlas. Available online at https://globalsolaratlas.info/support/about, checked on 8/18/2023.

GlobalWindAtlas (2023): Introduction: The Global Wind Atlas. Available online at https://globalwindatlas.info/en/about/introduction, checked on 8/18/2023.

González-Longatt, F.; Wall, P.; Terzija, V. (2012): Wake effect in wind farm performance: Steady-state and dynamic behavior. In *Renewable Energy* 39 (1), pp. 329–338. DOI: 10.1016/j.renene.2011.08.053.

GPA (2022): Final Report: Pipelines vs Powerlines – A Technoeconomic Analysis in the Australian Context. GPA Engineering. Available online at https://www.apga.org.au/sites/default/files/uploaded-content/field_f_content_file/pipelines_vs_powerlines_-_a_technoeconomic_analysis_in_the_australian_context.pdf, checked on 11/27/2023.

GPF (2016): Saudi Arabia’s Oil and Gas Infrastructure, Geopolitical Futures. Available online at https://geopoliticalfutures.com/saudi-arabias-oil-and-gas-infrastructure/, checked on 8/8/2026.

Gupta, Neeraj (2016): A review on the inclusion of wind generation in power system studies. In *Renewable and Sustainable Energy Reviews* 59, pp. 530–543. DOI: 10.1016/j.rser.2016.01.009.

GWEC (2011): Global Wind Report - Annual market update 2010. Global Wind Energy Council (GWEC). Available online at https://gwec.net/wp-content/uploads/2012/06/GWEC_annual_market_update_2010_-_2nd_edition_April_2011.pdf, checked on 12/12/2023.

GWEC (2023): Global Wind Report 2023. Global Wind Energy Council (GWEC), checked on 12/12/2023.

Harrison-Atlas, Dylan; Lopez, Anthony; Lantz, Eric (2022): Dynamic land use implications of rapidly expanding and evolving wind power deployment. In *Environ. Res. Lett.* 17 (4), p. 44064. DOI: 10.1088/1748-9326/ac5f2c.

Harrison-Atlas, Dylan; Maclaurin, Galen; Lantz, Eric (2021): Spatially-Explicit Prediction of Capacity Density Advances Geographic Characterization of Wind Power Technical Potential. In *Energies* 14 (12), p. 3609. DOI: 10.3390/en14123609.

Heinemann, Christoph; Mendelevitch, Roman; Ritter, David; Jakob, Michael; Dünzen, Kaya; Krieger, Susanne (2022a): Hydrogen Fact Sheet – North African Countries – Morocco | Algeria | Tunisia | Egypt | Mauritania. Institut für angewandte Ökologie (Öko-Institut e. V.). Available online at https://www.oeko.de/publikation/hydrogen-fact-sheet-north-african-countries/, checked on 11/23/2023.

Heinemann, Christoph; Ritter, David; Mendelevitch, Roman; Dünzen, Kaya (2022b): Hydrogen fact sheet – Gulf Cooperation Countries (GCC) – Saudi-Arabia | Oman | United Arab Emirates | Qatar | Kuwait | Bahrain. Institut für angewandte Ökologie (Öko-Institut e. V.). Available online at https://www.oeko.de/en/publications/hydrogen-fact-sheet-gulf-cooperation-countries-gcc, checked on 11/23/2023.

Hoffmann, Patrick; Mier, Mathias (2022): Wind Turbine Placement and Externalities, ifo Institute. Available online at https://www.ifo.de/DocDL/wp-2022-369-hoffmann-mier-wind-power.pdf, checked on 7/17/2023.

IC-SA (2023): Industrial Infrastructure, Saudi Industrial Center. Available online at https://www.ic.gov.sa/en/invest-in-saudi-arabia/transportation-network/, checked on 8/8/2023.

IEA (2019): The future of hydrogen - Seizing today's opportunities. International Energy Agency. Available online at https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf, checked on 10/31/2023.

IEA (2021): Net zero by 2050 - A roadmap for the global energy sector. International Energy Agency. Available online at https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf, checked on 12/12/2023.

IRENA (2018): Hydrogen from renewable power: Technology outlook for the energy transition. International Renewable Energy Agency (IRENA). Available online at https://www.irena.org/-/media/files/irena/agency/publication/2018/sep/irena_hydrogen_from_renewable_power_2018.pdf, checked on 11/27/2023.

IRENA (2020): Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal. International Renewable Energy Agency (IRENA). Available online at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf, checked on 10/16/2023.

IRENA (2021a): Green hydrogen supply – A guide to policy making. Available online at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/May/IRENA_Green_Hydrogen_Supply_2021.pdf, checked on 10/10/2023.

IRENA (2021b): Making the breakthrough: Green hydrogen policies and technology costs. International Renewable Energy Agency (IRENA). Available online at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_Hydrogen_breakthrough_2021.pdf?la=en&hash=40FA5B8AD7AB1666EECBDE30EF458C45EE5A0AA6, checked on 11/27/2023.

IRENA (2022): Geopolitics of the energy transformation. The hydrogen factor. Abu Dhabi: IRENA.

Janzow, Natalie; Blank, Thomas Koch; Tatatenko, Oleksiy (2022): Tackling Investment Risks to Accelerate Green Hydrogen Deployment in the EU. Available online at https://rmi.org/tackling-investment-risks-to-accelerate-green-hydrogen-deployment-in-the-eu/, checked on 2/24/2024.

Jensen, Cathrine Ulla; Panduro, Toke Emil; Lundhede, Thomas Hedemark (2014): The Vindication of Don Quixote: The Impact of Noise and Visual Pollution from Wind Turbines. In *Land Economics* 90 (4), pp. 668–682. Available online at http://www.jstor.org/stable/24243974.

Kaldellis, J. K.; Apostolou, D.; Kapsali, M.; Kondili, E. (2016): Environmental and social footprint of offshore wind energy. Comparison with onshore counterpart. In *Renewable Energy* 92, pp. 543–556. DOI: 10.1016/j.renene.2016.02.018.

Koch, Natalie (2022): Gulf Hydrogen Horizons. Why are Gulf oil and gas producers so keen on hydrogen?

Kontur (2023): Population Density Dataset. Available online at https://www.kontur.io/portfolio/population-dataset/, checked on 8/18/2023.

Kost, Christoph; Shammugam, Shivenes; Fluri, Verena; Peper, Dominik; Memar, Aschkan Davoodi; Schlegl, Thomas (2021): Levelized Cost of Electricity- Renewable Energy Technologies. Available online at https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/EN2021_Fraunhofer-ISE_LCOE_Renewable_Energy_Technologies.pdf, checked on 8/11/2023.

Krohn, Soren; Awerbuch, Shimon; Morthorst, Paul Erik; Blanco, Isabel; Van Hulle, Frans; Kjaer, Christian; Clifford, Sarah (2009): The economics of wind energy - A report by the European Wind Energy Association. Available online at https://www.ewea.org/fileadmin/files/library/publications/reports/Economics_of_Wind_Energy.pdf, checked on 7/24/2023.

Layton, Bradley E. (2008): A Comparison of Energy Densities of Prevalent Energy Sources in Units of Joules Per Cubic Meter. In *International Journal of Green Energy* 5 (6), pp. 438–455. DOI: 10.1080/15435070802498036.

Lloret, Josep; Turiel, Antonio; Solé, Jordi; Berdalet, Elisa; Sabatés, Ana; Olivares, Alberto et al. (2022): Unravelling the ecological impacts of large-scale offshore wind farms in the Mediterranean Sea. In *The Science of the total environment* 824, p. 153803. DOI: 10.1016/j.scitotenv.2022.153803.

Mahdy, Mostafa; Bahaj, AbuBakr S.; Alghamdi, Abdulsalam S. (2016): Offshore Wind Energy Potential Around the East Coast of the Red Sea, KSA. In Manuel Romero, Daniel Mugnier, David Renné, Ken Guthrie, Steven Griffiths (Eds.): Proceedings of SWC2017/SHC2017. ISES Solar World Conference 2017 and the IEA SHC Solar Heating and Cooling Conference for Buildings and Industry 2017. Abu Dhabi, 10/29/2017 - 11/2/2017. Freiburg, Germany: International Solar Energy Society, pp. 1–11.

Martin, Polly (2023): Neom formally reaches FID on giant green hydrogen complex as partners ink financing deals worth $8.4bn. Available online at https://www.hydrogeninsight.com/production/neom-formally-reaches-fid-on-giant-green-hydrogen-complex-as-partners-ink-financing-deals-worth-8-4bn/2-1-1454268, checked on 12/12/2023.

McWilliams, Ben; Zachmann, Georg (2023): Renewable hydrogen in Germany, Poland, and Portugal. Available online at https://www.euki.de/wp-content/uploads/2023/09/Renewable-Hydrogen-in-Germany-Poland-Portugal_2023.pdf, checked on 1/15/2024.

Mezősi, András; Kácsor, Enikő; Diallo, Alfa (2023): Projects of common interest? Evaluation of European electricity interconnectors. In *Utilities Policy* 84, p. 101642. DOI: 10.1016/j.jup.2023.101642.

Mohammed Hamidaddin; Muhammad Said Abdallah; Mudhaffar Al-Hajji; Nawaf Al-Atallah (2017): "PETE411-Senior Design Project" Presentation (Development of a Gas Condensate Reservoir).

NEOM (2023): Neom green hydrogen company completes financial close at a total investment value of VUS 8.4 billion in the world's largest carbon-free green hydrogen plant. Available online at https://www.neom.com/en-us/newsroom/neom-green-hydrogen-investment, checked on 12/12/2023.

Nigbur, Florian; Robinius, Martin; Wienert, Patrick; Deutsch, Matthias (2023): Levelised cost of hydrogen - Making the application of the LCOH concept more consistent and more useful. Available online at https://static.agora-energiewende.de/fileadmin/Projekte/2022/2022-12-10_Trans4Real/A-EW_301_LCOH_WEB.pdf, checked on 8/17/2023.

OpenTopography (2013): Shuttle Radar Topography Mission (SRTM) Global.

OSM (2023): GCC states - Open Street Map. Available online at https://download.geofabrik.de/asia/gcc-states.html, checked on 8/18/2023.

OWID (2023a): Levelized cost of energy by technology. Available online at https://ourworldindata.org/grapher/levelized-cost-of-energy, checked on 12/12/2023.

OWID (2023b): Solar (photovoltaic) panel prices. Available online at https://ourworldindata.org/grapher/solar-pv-prices?yScale=linear, checked on 12/12/2023.

OWID (2023c): Solar (photovoltaic) panels cumulative capacity. Available online at https://ourworldindata.org/grapher/solar-pv-cumulative-capacity, checked on 12/12/2023.

Piotrowski, Pawel; Salame, Joelle (2023): Middle East – The H2 Handbook: Legal, regulatory, policy and commercial issues impacting the future of hydrogen. Available online at https://marketingstorageragrs.blob.core.windows.net/webfiles/Hydrogen-Handbook_MiddleEast.pdf, checked on 12/12/2023.

Preuster, Patrick; Papp, Christian; Wasserscheid, Peter (2017): Liquid Organic Hydrogen Carriers (LOHCs): Toward a Hydrogen-free Hydrogen Economy. In *Accounts of chemical research* 50 (1), pp. 74–85. DOI: 10.1021/acs.accounts.6b00474.

Qamar Energy (2018): Saudi Arabia energy needs and nuclear power. Available online at https://npolicy.org/Articles/March%202018%20Drafts/Mills_Saudi_Arabia_Feb18.pdf, checked on 10/11/2023.

Reksten, Anita H.; Thomassen, Magnus S.; Møller-Holst, Steffen; Sundseth, Kyrre (2022): Projecting the future cost of PEM and alkaline water electrolysers; a CAPEX model including electrolyser plant size and technology development. In *International Journal of Hydrogen Energy* 47 (90), pp. 38106–38113. DOI: 10.1016/j.ijhydene.2022.08.306.

Rhodes, Joshua D.; King, Carey; Gulen, Gürcan; Olmstead, Sheila M.; Dyer, James S.; Hebner, Robert E. et al. (2017): A geographically resolved method to estimate levelized power plant costs with environmental externalities. In *Energy Policy* 102, pp. 491–499. DOI: 10.1016/j.enpol.2016.12.025.

Ritchie, Hannah; Rosado, Pablo (2020): Electricity Mix Electricity Mix - Explore data on where our electricity comes from, and how this is changing. Available online at https://ourworldindata.org/electricity-mix, checked on 12/12/2023.

Roach, Samuel; Park, Se Myung; Gaertner, Evan; Manwell, James; Lackner, Matthew (2020): Application of the New IEC International Design Standard for Offshore Wind Turbines to a Reference Site in the Massachusetts Offshore Wind Energy Area. In *J. Phys.: Conf. Ser.* 1452 (1), p. 12038. DOI: 10.1088/1742-6596/1452/1/012038.

S&P Global (2023): The cost of renewables will continue to fall, this is why - Long-term cost drivers for solar, wind and energy storage. Available online at https://cdn.ihsmarkit.com/www/pdf/0423/SPGCI-The-Cost-of-Renewables-Will-Continue-to-Fall-Report.pdf, checked on 8/11/2023.

Salam, Mohammad Asif; Khan, Sami A. (2018): Transition towards sustainable energy production – A review of the progress for solar energy in Saudi Arabia. In *Energy Exploration & Exploitation* 36 (1), pp. 3–27. DOI: 10.1177/0144598717737442.

Satymov, Rasul; Bogdanov, Dmitrii; Breyer, Christian (2022): Global-local analysis of cost-optimal onshore wind turbine configurations considering wind classes and hub heights. In *Energy* 256, p. 124629. DOI: 10.1016/j.energy.2022.124629.

Saunders, Paul J. (2020): Land use requirements of solar and wind power generation: understanding a decade of academic research. Available online at https://www.innovationreform.org/wp-content/uploads/2020/10/1909-Energy-Reform-Land-Use-Requirements_digital.pdf, checked on 8/7/2023.

Sawant, Manisha; Thakare, Sameer; Rao, A. Prabhakara; Feijóo-Lorenzo, Andrés E.; Bokde, Neeraj Dhanraj (2021): A Review on State-of-the-Art Reviews in Wind-Turbine- and Wind-Farm-Related Topics. In *Energies* 14 (8), p. 2041. DOI: 10.3390/en14082041.

Schimmel, Matthias; Bietenholz, Diego; Steinbacher, Karoline; Braun, Jan Frederik; Shabaneh, Rami; Roychoudhury, Jitendra; Saxena, Saumitra (2022): Hydrogen cooperation potential between Saudi Arabia and Germany - A joint study by the Saudi-German energy dialogue. Available online at https://www.bmwk.de/Redaktion/EN/Downloads/J/joint-study-saudi-german-energy-dialogue.html, checked on 1/23/2023.

Schreyer, Felix; Ueckerdt, Falko; Pietzcker, Robert; Rodrigues, Renato; Rottoli, Marianna; Madeddu, Silvia et al. (2024): Distinct roles of direct and indirect electrification in pathways to a renewables-dominated European energy system. In *One Earth* 7 (2), pp. 226–241. DOI: 10.1016/j.oneear.2024.01.015.

Schröder, Jonas; Jörling, Korinna; Francy, Reshma Carmel; Al Falasi, Fatima; Von Zitzewitz, Ellen; Zangerl, Karin (2021): The role of Hydrogen for the energy transition in the UAE and Germany - A joint study by the Emirati-German Energy Partnership. Available online at https://www.energypartnership-uae.org/fileadmin/user_upload/vae/publications/The_Role_of_Hydrogen_for_the_Energy_Transition_in_the_UAE_and_Germany.pdf, checked on 1/24/2023.

Schwanitz, Valeria Jana; Wierling, August (2016): Offshore wind investments – Realism about cost developments is necessary. In *Energy* 106, pp. 170–181. DOI: 10.1016/j.energy.2016.03.046.

Seck, Gondia S.; Hache, Emmanuel; Sabathier, Jerome; Guedes, Fernanda; Reigstad, Gunhild A.; Straus, Julian et al. (2022): Hydrogen and the decarbonization of the energy system in europe in 2050: A detailed model-based analysis. In *Renewable and Sustainable Energy Reviews* 167, p. 112779. DOI: 10.1016/j.rser.2022.112779.

Shiptraffic (2023): Shiptraffic - Sea distance calculator. Available online at http://www.shiptraffic.net/, checked on 10/29/2023.

Sprenger, Tobias; Wild, Patricia; Pickert, Lena (2023): H2-Geopolitics: Geopolitical risks in global hydrogen trade. Available online at https://www.ewi.uni-koeln.de/en/publications/geopolitical-risks-in-global-hydrogen-trade/#:~:text=Geopolitical%20risks%20are%20closely%20related,chain%20form%20another%20risk%20dimension., checked on 1/23/2024.

Stevens, Richard J.A.M.; Gayme, Dennice F.; Meneveau, Charles (2016): Effects of turbine spacing on the power output of extended wind-farms. In *Wind Energy* 19 (2), pp. 359–370. DOI: 10.1002/we.1835.

Sundaram, Arunachalam; Mas'ud, Abdullahi Abubakar; Al Garni, Hassan Z.; Adewusi, Surajudeen (2020): Assessment of off-shore wind turbines for application in Saudi Arabia. In *IJECE* 10 (5), p. 4507. DOI: 10.11591/ijece.v10i5.pp4507-4513.

Swisher, Henry; Poon, John; Hatt, Belinda; Gerardi, Walter; Rachael, Millar (2019): Australia's pursuit of a large-scale hydrogen economy - Evaluating the economic viability of a sustainable hydrogen supply chain model. Available online at https://www.jacobs.com/sites/default/files/2022-03/Hydrogen_White_Paper_May2019.pdf, checked on 12/8/2023.

Sykes, V.; Collu, M.; Coraddu, A. (2023): A Review and Analysis of the Uncertainty Within Cost Models for Floating Offshore Wind Farms. In *Renewable and Sustainable Energy Reviews* 186, p. 113634. DOI: 10.1016/j.rser.2023.113634.

van Wijk, Ad; Wouters, Frank (2021): Hydrogen–The Bridge Between Africa and Europe. In Margot P. C. Weijnen, Zofia Lukszo, Samira Farahani (Eds.): Shaping an Inclusive Energy Transition. Cham: Springer International Publishing, pp. 91–119.

Voormolen, J. A.; Junginger, H. M.; van Sark, W.G.J.H.M. (2016): Unravelling historical cost developments of offshore wind energy in Europe. In *Energy Policy* 88, pp. 435–444. DOI: 10.1016/j.enpol.2015.10.047.

Vos, Maurice; Douma, Jochum; Van den Noort, Albert (2020): Study on the import of liquid renewable energy: Technology cost assessment. DNV GL. Available online at https://www.gie.eu/wp-content/uploads/filr/2598/DNV-GL_Study-GLE-Technologies-and-costs-analysis-on-imports-of-liquid-renewable-energy.pdf, checked on 10/29/2023.

Waheeb, S. A.; Al-Samarai, Riyadh A.; Alias, M. F. A.; Al-Douri, Y. (2023): Investigation of wind energy speed and power, and its impact of sustainability: Saudi Arabia a model. In *J. Umm Al-Qura Univ. Eng.Archit.* 14 (2), pp. 142–149. DOI: 10.1007/s43995-023-00019-z.

Weichenhain, Uwe; Albers, Bram; Billen, Dieter; Bernardo, Antonio; Castelein, Francois; Fages, Emmanuel et al. (2021): Hydrogen transportation | The key to unlocking the clean hydrogen economy. Roland Berger. Available online at https://www.rolandberger.com/publications/publication_pdf/roland_berger_hydrogen_transport.pdf, checked on 11/29/2023.

WETF (2023): Chapter 4: Global wind energy markets - The status of the global wind energy markets. Available online at https://www.wind-energy-the-facts.org/the-status-of-the-global-wind-energy-markets-6.html, checked on 12/12/2023.

WFO (2023): Global Offshore Wind Report 2022. World Forum Offshore Wind. Available online at https://wfo-global.org/wp-content/uploads/2023/03/WFO_Global-Offshore-Wind-Report-2022.pdf, checked on 10/13/2023.

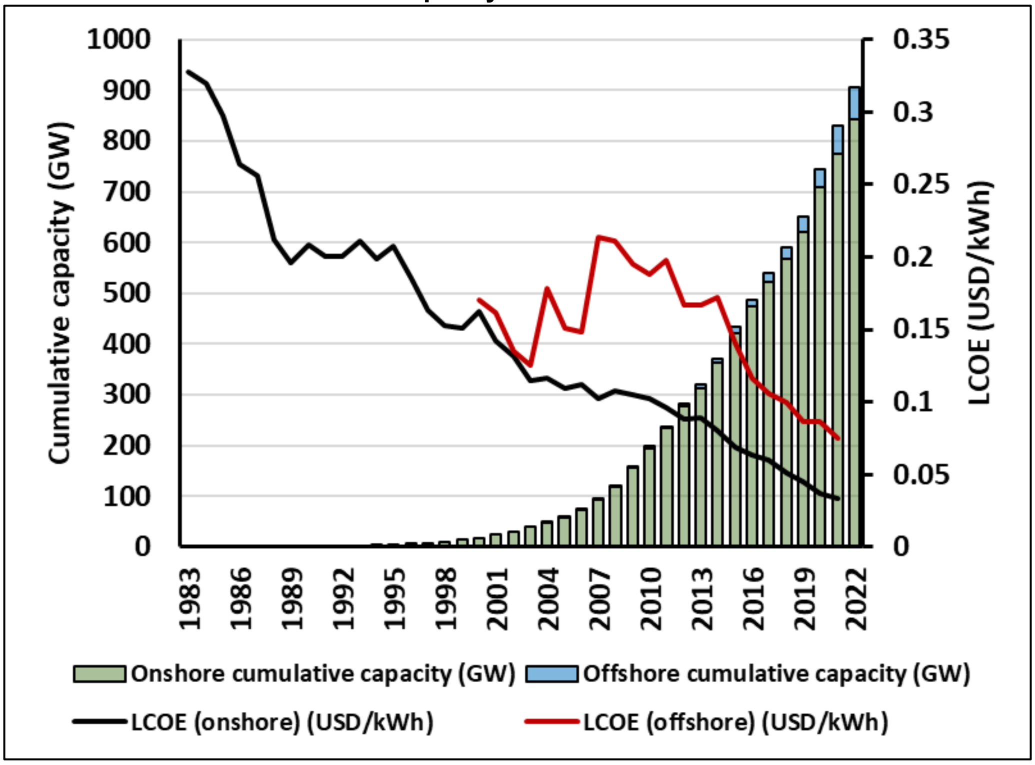
Wietschel, Martin; Bekk, Anke; Breitschopf, Barbara; Boie, Inga; Edler, Jakob; Eichhammer, Wolfgang et al. (2020): Opportunities and challenges when importing green hydrogen and synthesis products. Available online at https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2020/policy_brief_hydrogen.pdf, checked on 1/15/2024.

WPS (2023): World Port Source: Saudi Arabia - Satellite map of ports. Available online at http://www.worldportsource.com/ports/SAU.php, checked on 8/8/2023.

Yates, Jonathon; Daiyan, Rahman; Patterson, Robert; Egan, Renate; Amal, Rose; Ho-Baille, Anita; Chang, Nathan L. (2020): Techno-economic Analysis of Hydrogen Electrolysis from Off-Grid Stand-Alone Photovoltaics Incorporating Uncertainty Analysis. In *Cell Reports Physical Science* 1 (10), p. 100209. DOI: 10.1016/j.xcrp.2020.100209.

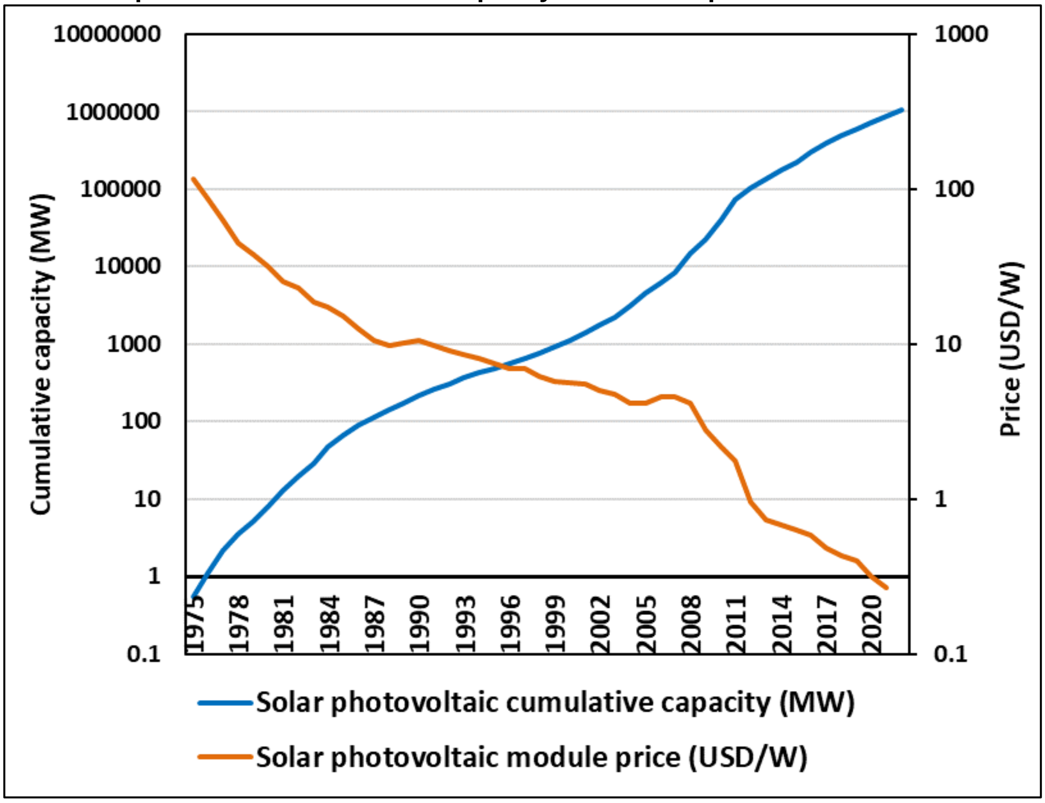
Appendix I: Supportive Figures

Figure A1: Wind turbines' cumulative capacity vs. levelized costs



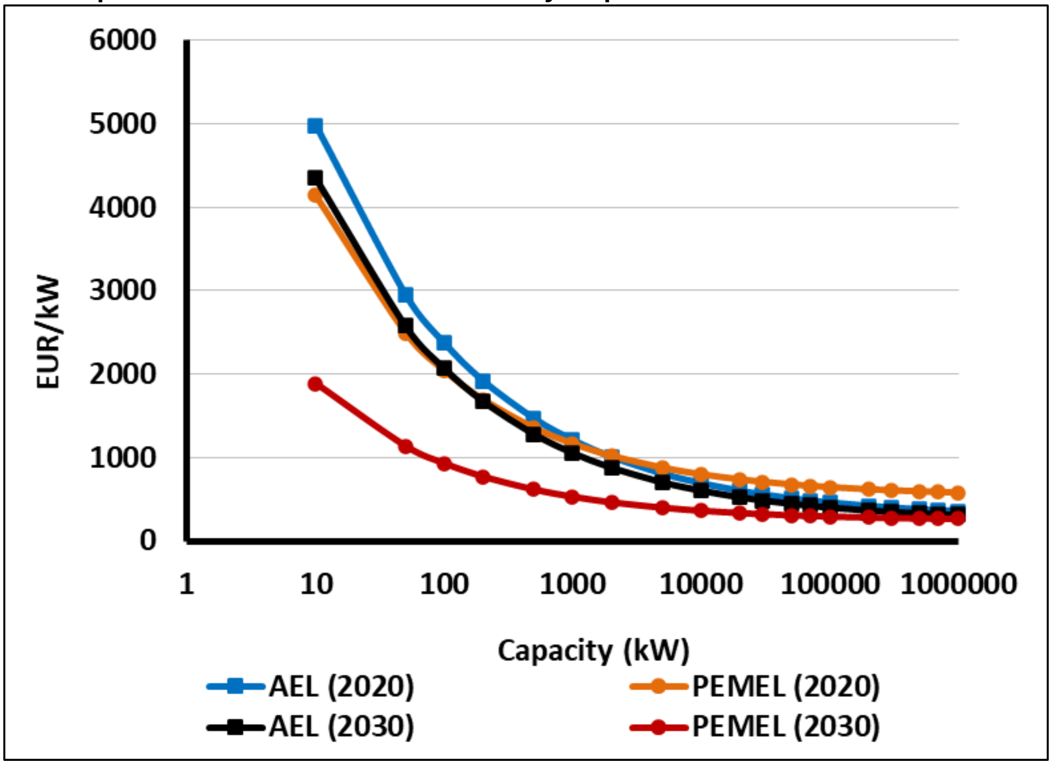
Source: Visualized based on (OWID 2023a; WETF 2023; GWEC 2011, 2023)

Figure A2: Solar photovoltaic cumulative capacity vs. module price



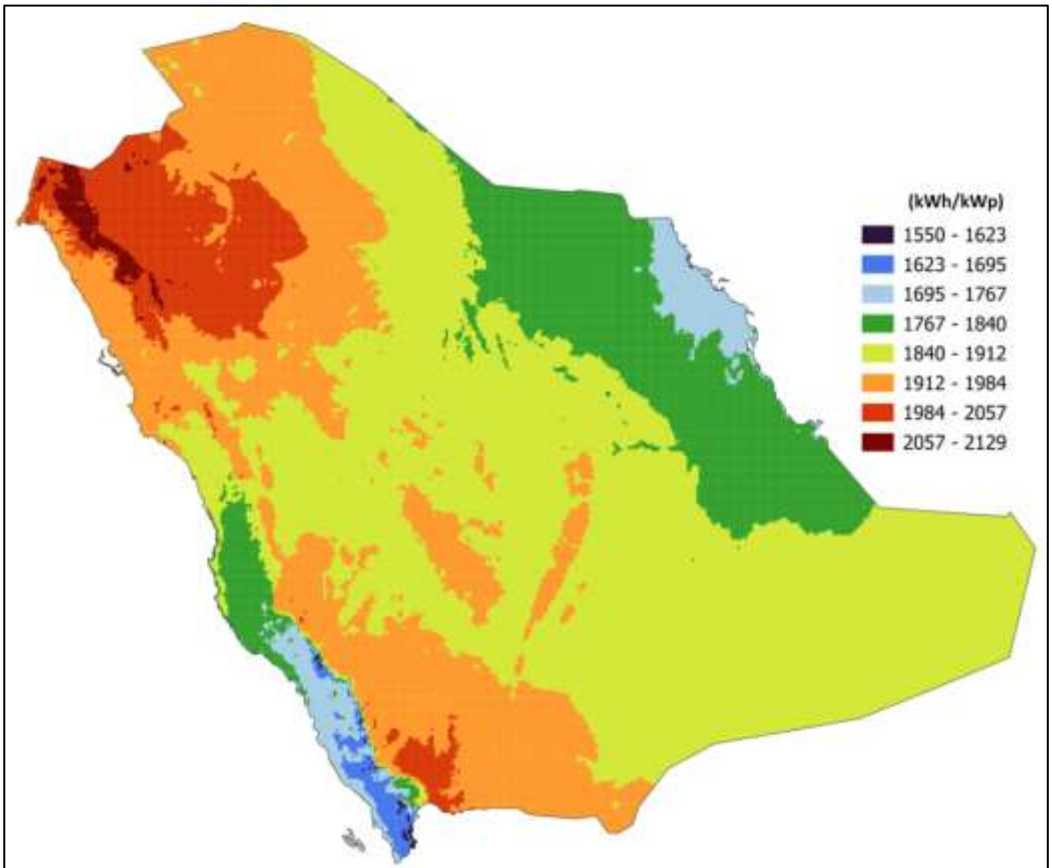
Source: Visualized based on (OWID 2023c, 2023b)

Figure A3: Capital costs of AEL and PEM electrolysis plants in 2020 and 2030



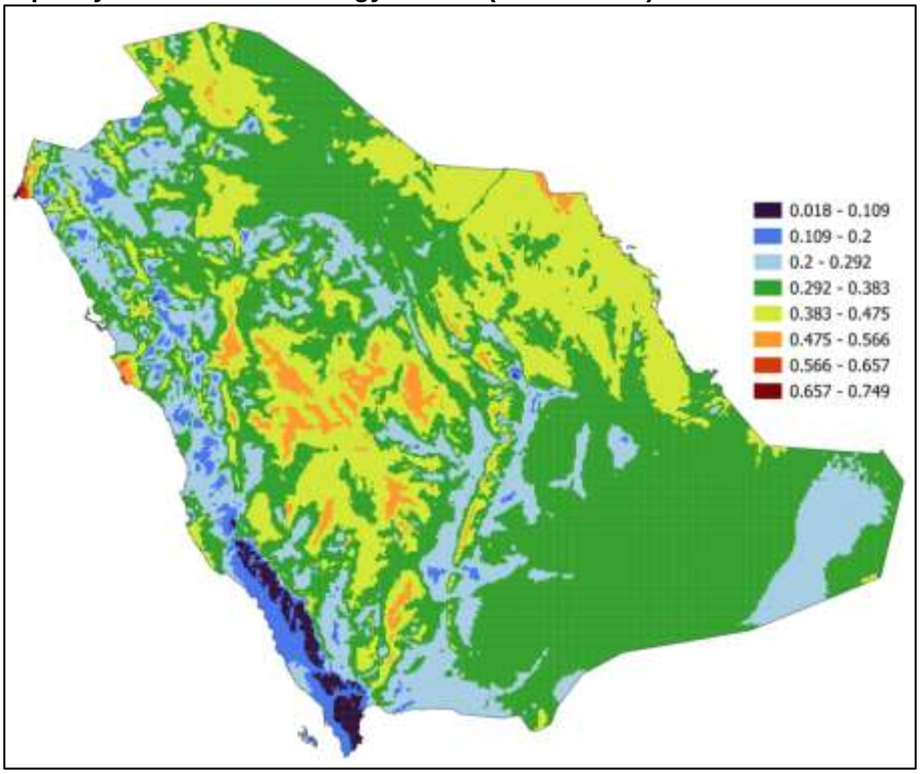
Source: Visualized based on (Reksten et al. 2022)

Figure A4: PVOUT in KSA



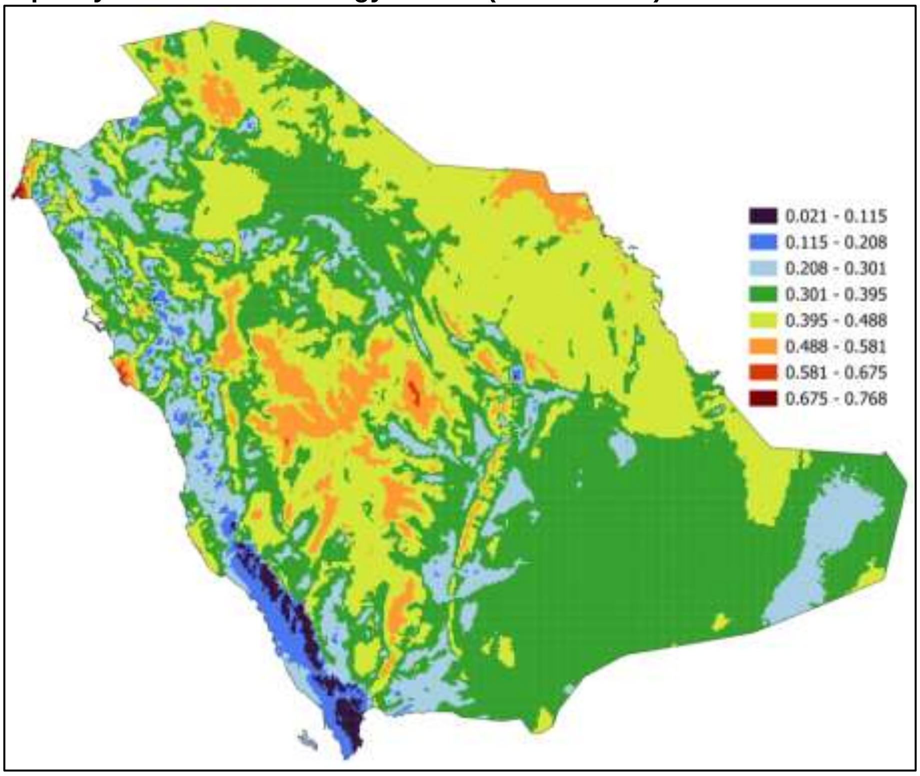
Source: Own analysis and visualization based on (GlobalSolarAtlas 2023)

Figure A5: Capacity factor of wind energy in KSA (class: IEC II)



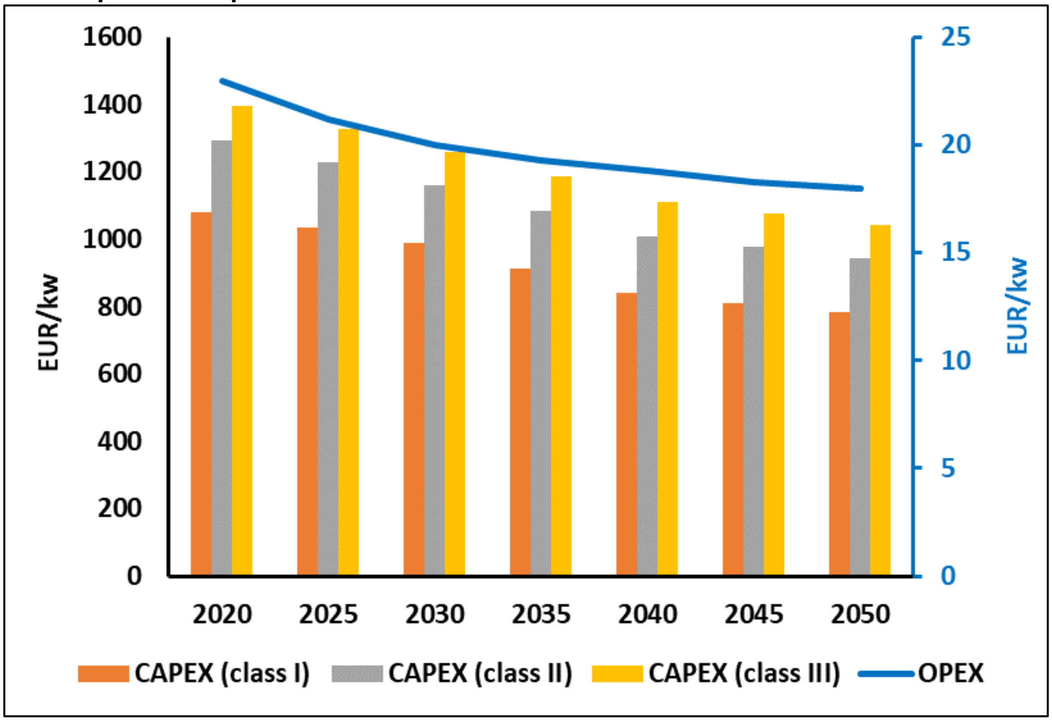
Source: Own analysis and visualization

Figure A6: Capacity factor of wind energy in KSA (class: IEC III)



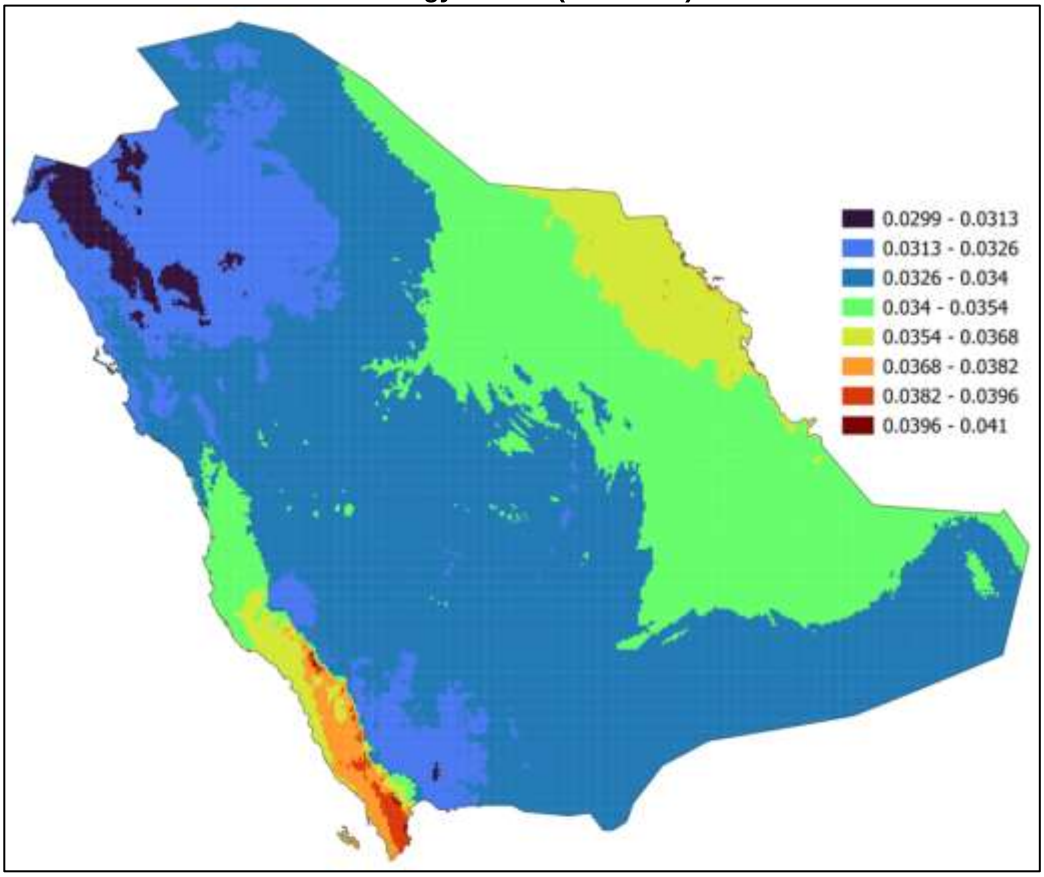
Source: Own analysis and visualization

Figure A7: Capital and operational costs of different wind turbine classes



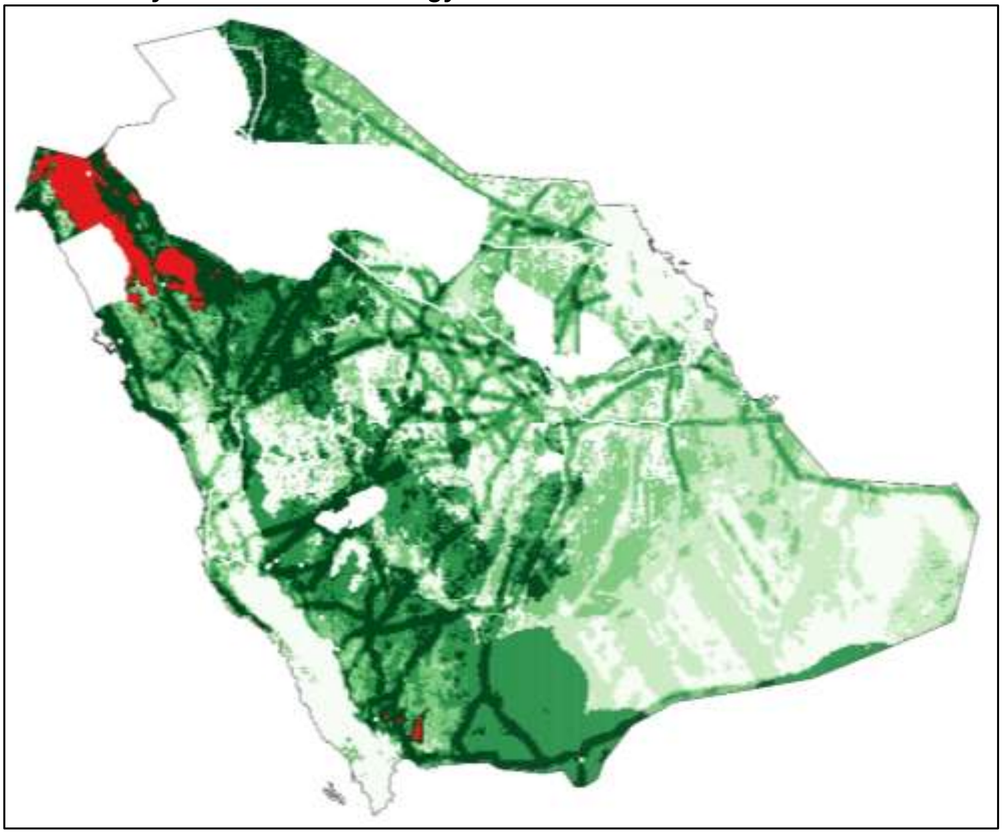
Source: Visualized based on (Satymov et al. 2022)

Figure A8: Levelized costs of solar energy in KSA (EUR/kWh)



Source: Own analysis and visualization based on (GlobalSolarAtlas 2023; Rhodes et al. 2017; Kost et al. 2021; Erichsen et al. 2019; Satymov et al. 2022)

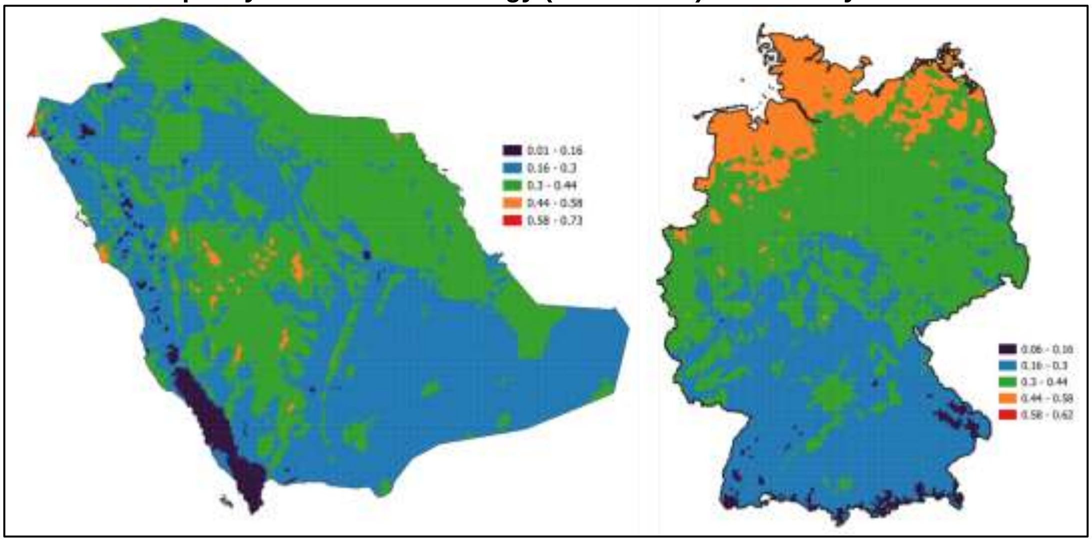
Figure A9: Suitability scores of solar energy in KSA



Source: Own analysis and visualization based on (GlobalSolarAtlas 2023; Kontur 2023; OSM 2023; Mahdy et al. 2016; OpenTopography 2013)

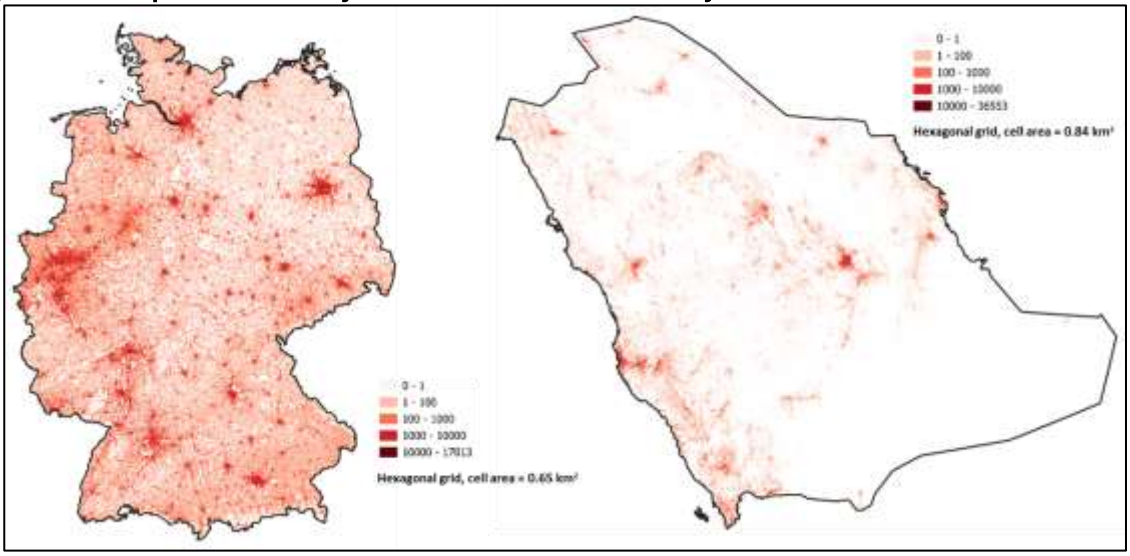
Note: Red areas represent score higher than 3.55 and LCOE lower than 0.0313

Figure A10: The capacity factor of wind energy (class: IEC I) in Germany vs. KSA



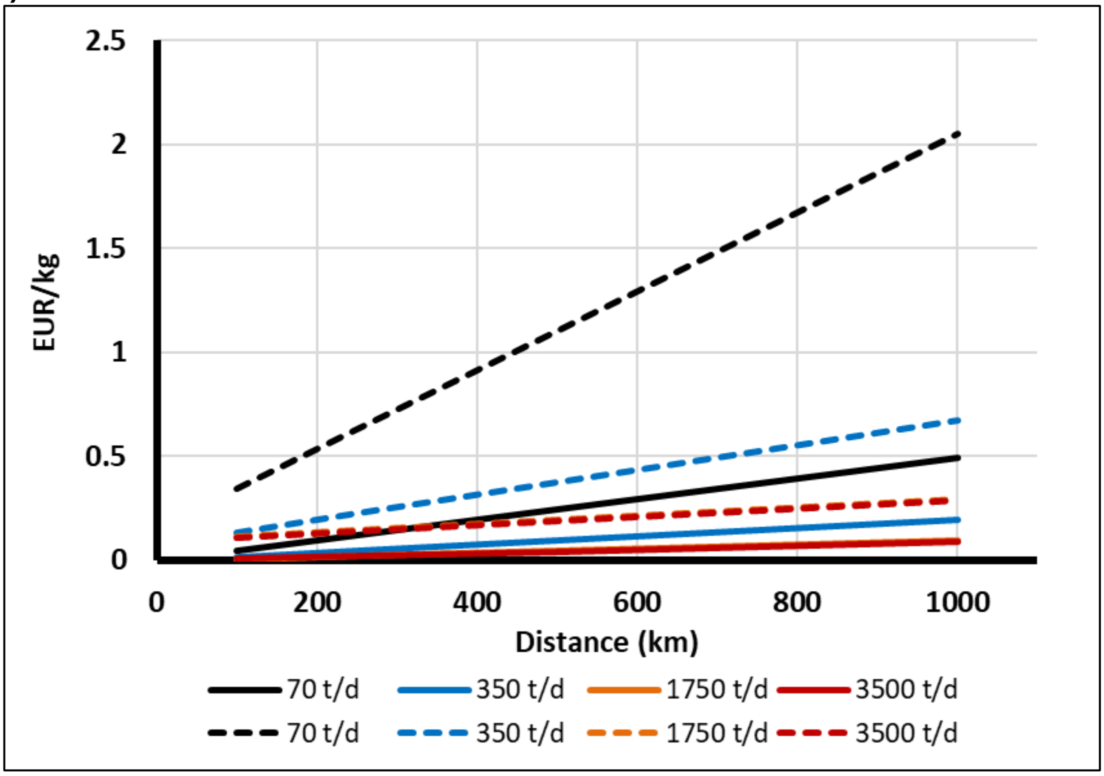
Source: Own analysis and visualization based on (GlobalWindAtlas 2023)

Figure A11: Population density and distribution in Germany and KSA



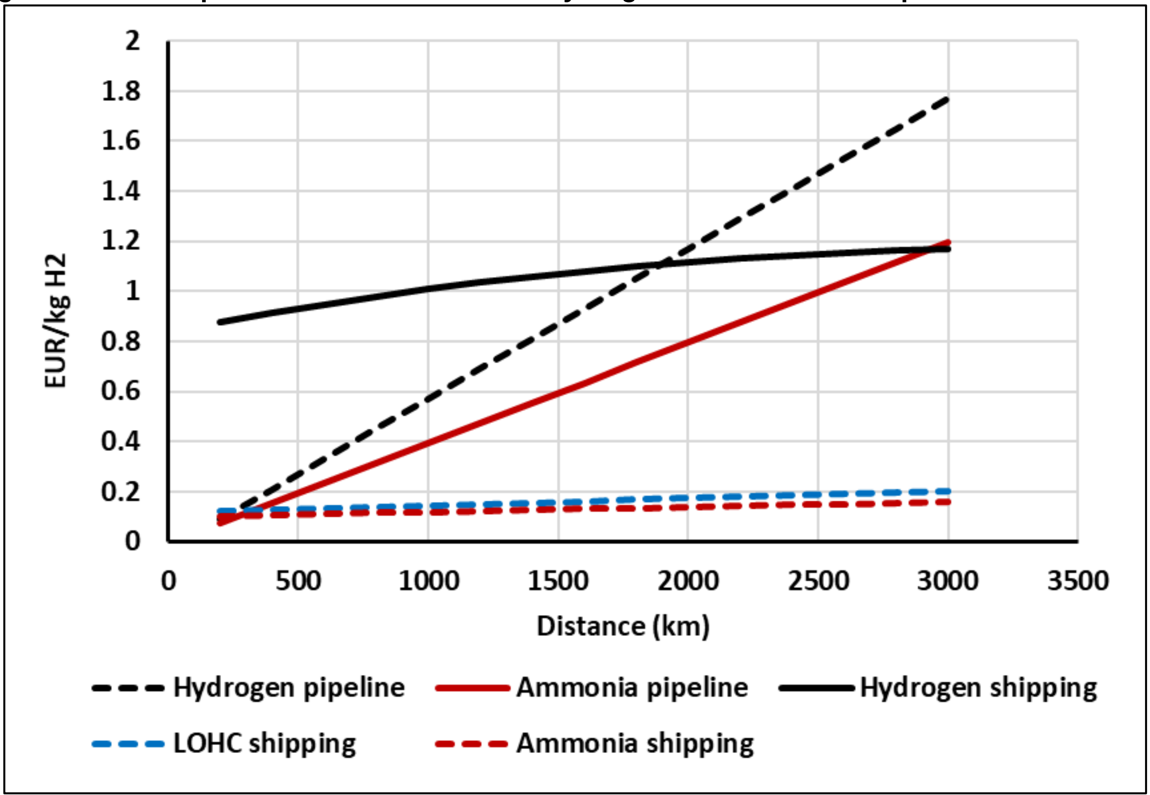
Source: Visualized based on (Kontur 2023)

Figure A12: Hydrogen transportation costs via pipeline (solid lines) vs. power lines (dotted lines)



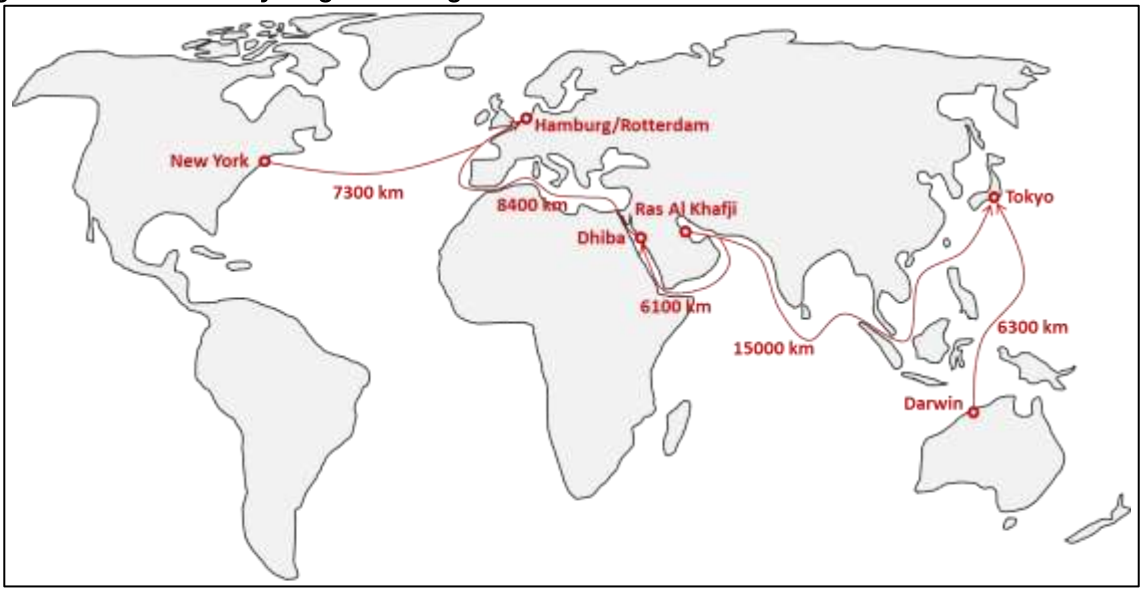
Source: Visualized based on (APGA 2022; GPA 2022)

Figure A13: Transportation costs of different hydrogen carriers and transportation modes



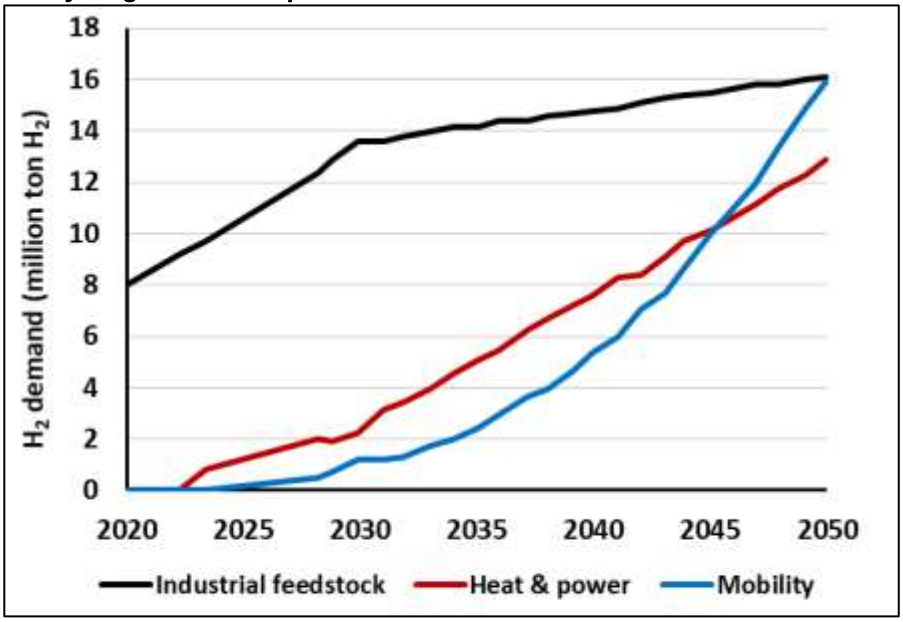
Source: Visualized based on (IEA 2019; Vos et al. 2020)

Figure A14: Potential hydrogen trading routes



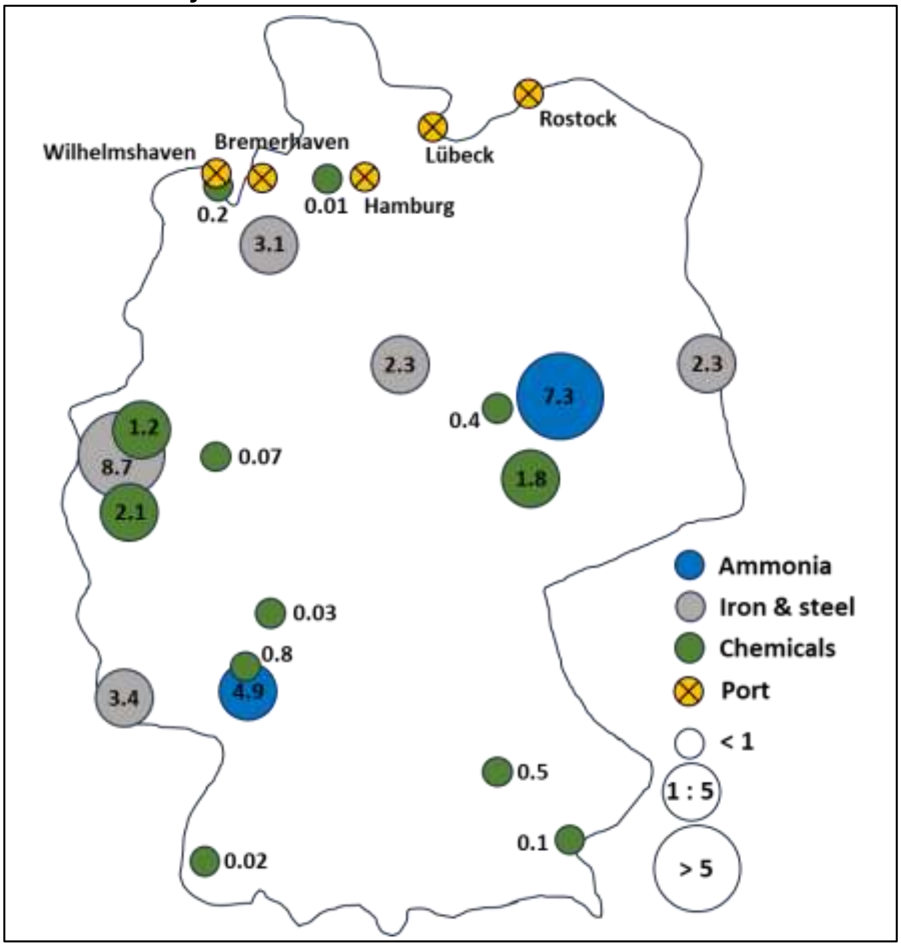
Source: Own visualization, distances are based on (Shiptraffic 2023)

Figure A15: EU hydrogen demand per sector



Source: visualized based on (Weichenhain et al. 2021)

Figure A16: Locations and quantities of hydrogen and ammonia demand (TWh/y) of the German industrial sector by 2050



Source: Visualized based on (Andreola et al. 2021)

Appendix II: Supportive Tables

Table 1: AHP criteria, scores and weights

Parameter	0	1	2	3	4	5	Importance /Weight
Railway	< 250 m	-	-	-	-	-	-
Natural reserves	inside	-	-	-	-	-	-
Airports	<2.5 km	-	-	-	-	-	-
Roads	< 500 m	> 8001 m	6001 : 8000 m	4001 : 6000 m	2001 : 4000 m	500 : 2000 m	10%
Power grid	< 250 m	> 8001 m	6001 : 8000 m	4001 : 6000 m	2001 : 4000 m	250 : 2000 m	10%
Slope	> 15°	10° : 15°	-	5° : 10°	-	0° : 5°	10%
Capacity factor (wind IEC I)	-	> 0.16	0.16 – 0.3	0.3 – 0.44	0.44 – 0.58	0.58 – 0.72	55%
Capacity factor (wind IEC II)	-	> 0.16	0.16 – 0.3	0.3 – 0.46	0.46 – 0.60	0.60 – 0.75	
Capacity factor (wind IEC III)	-	> 0.17	0.17 – 0.32	0.32 – 0.47	0.47 – 0.62	0.62 – 0.77	
Capacity factor (PV)	-	> 1700	1700 – 1800	1800 – 1900	1900 – 2000	2000 – 2050	
Population	-	100 k : 150 k	50 k : 100 k	1 k : 50 k	1 : 1 k	0 : 1	15%

Table 2: CAPEX and OPEX of different process (efficiency, losses and boil-off have been omitted)

Processes	CAPEX	Fixed OPEX	Variable OPEX
H2 to Ammonia	808 EUR/kW	2.5% CAPEX	0.14 kWh/kWh
Ammonia cracking	235 EUR/kW	3% CAPEX	0.14 kWh/kWh
LH2 shipping	4050 EUR/MWh	2.5% CAPEX	0.007776 EUR/MWh*km
Ammonia shipping	279 EUR/MWh	4.0% CAPEX	0.000080 EUR/MWh*km
H2 liquefaction	1350 EUR/kW	2.5% CAPEX	0.3 kWh/kWh
LH2 regasification	273 EUR/kW	2.5% CAPEX	0.01 kWh/kWh

Source: Vos et al. 2020

Appendix III: Key Equations

$$S = \sum_{i=1}^{n} C_i W_i \qquad (1)$$

$$\boldsymbol{Capital\ Recovery\ Factor\ (CRF)} = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (2)$$

$$\boldsymbol{LCOE} = \frac{Capital\ costs * CRF + O\&M_{fixed}}{8760 * CF} + O\&M_{variable} \qquad (3)$$

$$\boldsymbol{Annual\ Energy\ Production\ (AEP)} = P_{rated} * CF * 8760 \frac{hr}{year} \qquad (4)$$

$$\boldsymbol{LCOH} = \frac{Capital\ costs * CRF + O\&M_{fixed}}{Hydrogen\ production} + O\&M_{variable} \qquad (5)$$

$$\boldsymbol{LCOH} = \frac{Capital\ costs * CRF + O\&M_{fixed}}{(CF * 8760)(kWh) * \frac{1}{electricity\ req.for\ 1 \frac{kgH_2}{\boldsymbol{\eta_{electrolizer}}}} \left(\frac{kg\ H_2}{kWh}\right)} + O\&M_{variable} \qquad (6)$$

$$O\&M_{variable} = desalinated\ water + electricity + stack\ replacement \qquad (7)$$

$$OPEX\ (stack) = (Number\ of\ additional\ stackes) * cost \qquad (8)$$

$$OPEX\ (stack) = \left(\frac{Operating\ time - 40{,}000}{40{,}000}\right) * (cost) \qquad (9)$$

$$OPEX\ (stack) = \left(\frac{(25 * 24 * 365 * CF) - 40{,}000}{40{,}000}\right) * (0.2 * direct\ CAPEX) \qquad (10)$$

$$\frac{H_2\ demand\ (ton) * \left(\frac{MWh}{ton\ (H_2)} * \frac{1}{\eta_{electrolizer}}\right)}{8760 * Capacity\ Factor\ (CF)} * \frac{1}{Capacity\ density\ (CD) \left(\frac{MW}{km^2}\right)} \qquad (11)$$