# THE GREEN MACHINE

## GIS-BASED SITE SUITABILITY ANALYSIS FOR SOLAR AND WIND TO HYDROGEN POTENTIAL IN EUROPE AND MEDITERRANEAN REGION IN 2030 & 2040

**By**
**C. Groenewegen**

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C. Groenewegen

in partial fulfilment of the requirements for the degree of

**Master of Science**

in Sustainable Energy Technology
at the Delft University of Technology,

to be defended publicly on Thursday September 13, 2021, at 12:00 PM.

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*This thesis is not confidential and will be made public at 2-09-2021*

# ABSTRACT

Today's climate change creates a serious issue, which forces us to act by reducing Greenhouse Gas emissions across every sector. Making changes towards a sustainable world takes time and creates competition. Hydrogen has the potential to fuel a 'clean' economy because it is a carbon free energy carrier that can be produced from fossil fuels as well as renewable resources. This makes hydrogen the energy carrier of the future and a candidate to introduce into the European energy system. This thesis presents a geospatial techno-economic analysis on the potential of large scale low-cost green hydrogen production in Europe and North-Africa. Low-cost implies a production price lower than 1.5 €/kg. Large-scale means a minimum production amount of 1 million tons per year.

Current energy market developments show enough reasons and possibilities for green hydrogen production. Europe's energy system still consists mostly of fossil-based fuels and introducing green hydrogen could counterpart this state. But is there sufficient potential for low-cost large scale green hydrogen production? The research question is therefore: . *What is the potential for low-cost large-scale green hydrogen production in Europe and the Mediterranean region in 2030 & 2040?*

With GIS, a techno- and economical model the production price is visually depicted. System boundaries and design of a large-scale green hydrogen operation are needed for modelling. The geographical hydrogen potential visualizes the suitable areas. The technical hydrogen potential is determined by the yield of the solar and/or wind system. The economic hydrogen potential is determined by the Levelized costs of hydrogen.

There are enough areas in Europe and North-Africa for low-cost green hydrogen production in 2040. The solar PV system shows large potential against low-costs in North-Africa in 2040. The results show that for the solar scenario the LCOH ranges between 1.6 - 4.6 €/kg in 2030 and 0.9 - 2.7 €/kg in 2040. The wind turbine system can produce against low costs in North-Africa and North-Europe in 2030 and 2040. For wind the LCOH ranges between 1.5 – 5.3 €/kg in 2030 and 1 – 3.5 €/kg in 2040. The solar and wind combination shows the highest amount of potential against the lowest costs in 2040 and least amount of space used. The solar and wind combination shows the lowest price range in 2030 and 2040 of 1.5 – 3.7 €/kg and 0.7 – 1.8 €/kg. Including transport and storage costs for baseload hydrogen adds around 0.1 €/kg per 1000km for transport and 0.1 €/kg for salt cavern storage.

This research shows that large scale low-cost green hydrogen production has a substantial potential in South Europe and a very large potential in North-Africa. But North and Central European countries do not show sufficient large-scale low-cost hydrogen potential and will need to import from South Europe and North-Africa. The final potential and prices for the three different scenarios in North-, South Europe, and North Africa are depicted in the table below.

| **Region** | **Scenario** | **Potential 2040 (Mton) for <1.5 €/kg** |
|---|---|---|
| North-Europe | Solar | 0 |
| South-Europe | Solar | 1059 |
| North Africa | Solar | 26181 |
| North-Europe | Wind | 22 |
| South-Europe | Wind | 0 |
| North Africa | Wind | 2704 |
| North-Europe | Solar and wind | 1483 |
| South-Europe | Solar and wind | 1332 |
| North Africa | Solar and wind | 24006 |

The countries considered as North-Europe are Iceland, Norway, Sweden, Finland, Estonia, Latvia, Lithuania, Ireland, UK, Netherlands, Germany, Poland, Belgium, Luxembourg, Switzerland, Czech Republic, Austria, Slovenia, Hungary, and Slovak republic.
The countries considered as South-Europe are Portugal, Spain, France, Italy, Croatia, Romania, Turkey, Greece, Bosnia and Herzegovina, Serbia, Montenegro, Albania, Bulgaria, Moldova, and Macedonia.
The countries considered as North Africa are Western Sahara, Morocco, Algeria, Tunisia, Libya, Egypt, Israel, Jordan, Iraq, and Syria

Even with the rough estimations in the models, the results of this GIS-based research give a good first estimate for the geospatial large-scale low-cost hydrogen production potential. Using a geospatial techno-economic analysis proves to be a suitable method to visualize the future hydrogen production price. The geographical hydrogen potential is accurately depicted by the GIS program, but it comes with its difficulties with datasets. The technical hydrogen potential is based on today’s knowledge of future technology, but the factors may vary in the future. With the used cost input data, the levelized cost of electricity and hydrogen are comparable with other studies. The area size criterion used in the GIS modelling needs to be analyzed in more detail to show the total production potential of an area.

# PREFACE

This document is the result of 10 months of research on low-cost large-scale hydrogen system implementation in Europe and Mediterranean region. For the degree of Sustainable Energy Technology at the faculty of Electrotechniek, Wiskunde & Informatica (EWI).

When I hand in this document it will mean an end of an era and a start of a new journey in life. The past years and this thesis have shaped me to the person I am today. I have enjoyed the times I had in Delft and liked studying here.

This research is not something I have done on my own. With the help of friends and family that supported me during my thesis, while the Corona virus was active, really helped to push me in the right direction. For the research I would first like to thank Prof. Dr. Ad van Wijk who started this whole project as a part of his own research. His research will be used to push legislations in the hydrogen industry and help the EU and companies to invest in this industry. During my thesis we met numerous times and some more at the end, which helped get realistic values. Every time I iterated the model the results showed something surprising and gave us some food for thought. During these iterations I came to understand how conceptual the hydrogen market is and that we are only standing at the foot of it. Also, I would like to thank Dongliang Peng for helping me create my model in ArcGIS Pro. He really took the time, gave feedback, and directed me to other professors on the matter to get the model working. In addition, I would like to thank him for introducing me to Prof. Peter van Oosterom, who invited me to give a presentation in his symposium for educational purposes for his staff. Furthermore, I would like to thank my mother, brother and aunt who supported me mentally when things did not go as planned. Without them it was difficult to stay motivated at times. Also, I would like to thank my roommates at the Jungalow who offered me enough distraction during the final months of my research, helped me with my modelling and my work. In addition, I want to give a little shout out to Hugo for helping me during stressful times and with the countless amounts of random moments that brought a smile on my face during this research. Doing this research was not easy during Corona, as I had to stay inside most of the time, but I must say by doing this I have tested my limits and pushed my boundaries as a human being in a positive way.

*Charlie David Groenewegen*

*Delft, September 2021*

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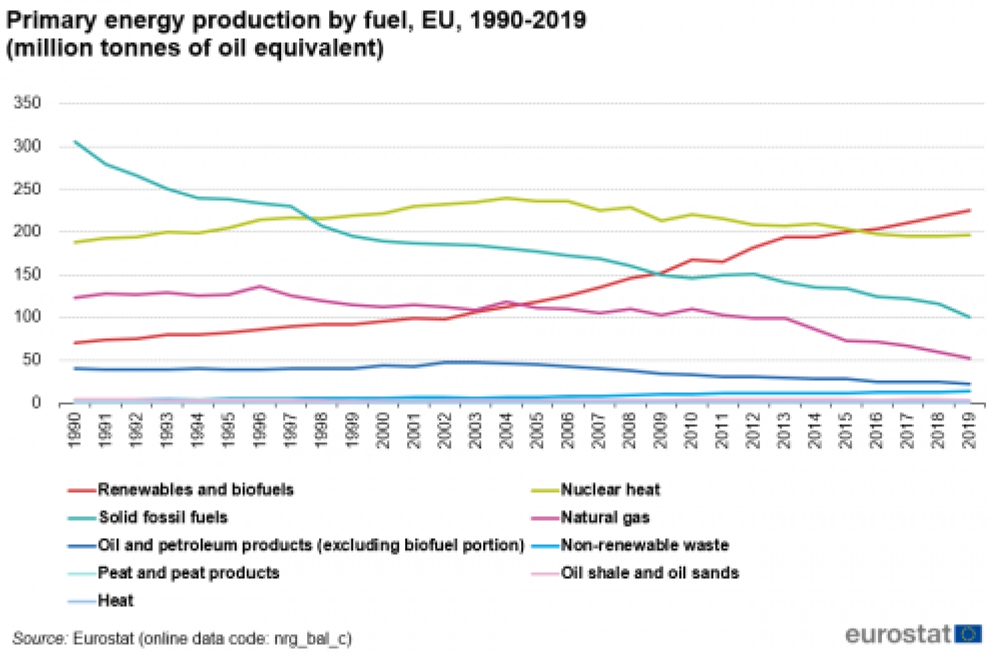
# 1 INTRODUCTION

This chapter will introduce the main parts of this research. First, in 1.1 the topic and context are discussed to give an understanding of this report by identifying the general problem. In section 1.2 the current state of literature regarding the subject and problem is discussed. Finally, in section 1.3 the literature gaps are shown, and this results in several key research questions that, when answered, can provide a solution for the main issue of this report.

## 1.1 IDENTIFYING THE PROBLEM

World energy demand has increased in the last years and this trend is to continue in the future, including for European countries. Europe is a net energy importer, with 61% of energy needs being imported in 2019. This dependency on energy imports forms the background for policy concerns relating to security of energy supplies. The European consumption of fossil fuels continues to decrease each year, especially gas production. However, oil and gas remain the first and second largest energy source in Europe. Figure 1 shows the primary energy production by fuel for the EU between 1990 and 2019. An increase for renewable energy of 48.3% is seen, which shows that renewable energy is the largest primary form of energy produced.



Primary energy production by fuel, EU, 1990-2019
(million tonnes of oil equivalent)

*Source:* Eurostat (online data code: nrg_bal_c)

Figure 1 Primary energy production by fuel for the EU between 1990-2019. The increase in renewables and biofuel for fuel production and the decrease in carbon-based fuels indicates a change to a greener market [3]

Other sources of produced fuels in figure 1 are in decline. This low rate of energy production resulted in an increase of energy import. The amount of imported gas has doubled over the period 1990-2019. Figure 2 shows the import and export of energy products between 1990-2019. Crude oil and natural gas are the largest factors of import. Levels of export are much lower between 1990-2019 due to lower energy production. It should be noted that import and export also include intra-EU trade [3]. Although Europe is importing more renewable energy, due to lack of space for renewable energy and a high population density, it will continue to be dependent until mid-century and beyond [65].

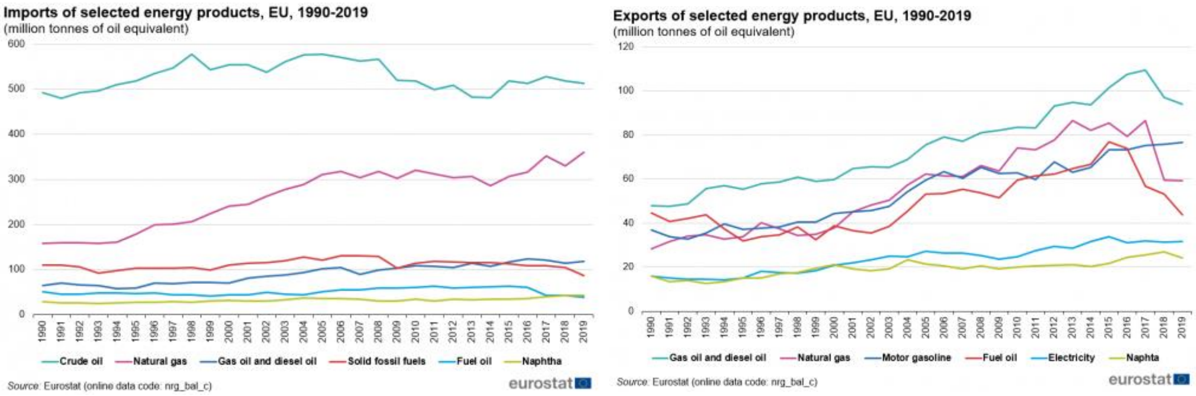


**Figure 2 Imports and Exports of energy products in the EU between 1990-2019. Gas oil and diesel oil are the most imported and exported energy product between 1990 and 2019. [3]**

Today's climate change creates a serious issue, which forces us to act by reducing Greenhouse Gas emissions across every sector. To meet the obligations of the Paris Agreement in 2050 the EU member states have set targets for 2030 and 2050 to create a more sustainable Europe. A suggestion to reach these targets is to replace natural gas by hydrogen. Making changes towards a more sustainable world takes time and creates competition. Several scenarios exist for Europe's future energy system in 2050 for introducing (green) hydrogen, such as 'Hydrogen 2030 : The Blueprint' by Hydrogen Europe [38], 'Hydrogen Roadmap Europe' by FCH JU [62], 'Hydrogen Act – Towards the creation of the European hydrogen economy' by Hydrogen Europe [66], and 'Net zero by 2050 – A roadmap for the Global Energy Sector' by IEA [67]. Hydrogen has the potential to fuel a 'clean' economy because it is a carbon free energy carrier that can be produced from fossil fuels as well as renewable energy resources [68]. There is an ever-growing interest in green hydrogen due to the decline in renewable energy prices. The hydrogen market is getting a strong momentum as a corner stone for the energy transition as in 2021 more than 30 countries have released their own hydrogen roadmaps. This movement  has ensured that over 200 hydrogen projects have been announced, together with multiple investment plans, and governmental commitment to large public funding of these projects. This will, in combination with dropping renewable energy prices, accelerate the cost reductions for hydrogen production, distribution, transmission, retail, and end-applications [6].

However, it is not yet thoroughly researched what the effect of introducing green hydrogen into the European energy system will be on the import and export of energy products in the future.

Hydrogen allows for cost-efficient energy transport over long distances and cost-effective storage for large amounts of energy. Now, green hydrogen can be produced at low costs due to decreasing renewable energy prices. Achieving a European energy system based partly on green hydrogen can be achieved. Introducing green hydrogen into the European energy system can have a certain positive effect on the import and export of energy products. But this effect on the energy system is determined by the price per unit of this sustainable energy carrier [6]. Hydrogen and electricity infrastructure with seasonal hydrogen storage and day-night electricity storage, will be necessary to realize a sustainable, zero-emission and cost-effective energy system in the future [10].

Therefore, production, transport, and storage are of great importance to determine the overall price per region where green hydrogen is produced. The scale of this project requires a large amount of available space, with excellent resources, to make it competitive to fossil fuel produced hydrogen [6].

To introduce green hydrogen at such a large scale the amount of area needed is assumed to be large. The potential is now only estimated by looking at resource information, but this doesn't show the exact amount of available area. So, it is questionable how one can determine the exact amount of available space and how much space is really needed for these large-scale projects.

This calls for an analysis of the combination of economic, technical, and geographic aspects for determining the production price per region for green hydrogen. By knowing the overall production price, the effect on Europe's energy system of introducing this green energy carrier can be determined.

## 1.2 LITERATURE REVIEW

### 1.2.1. SOLAR- AND WIND ELECTRICTY PRICES

#### LOW RENEWABLE ENERGY PRICES MAKE GREEN HYDROGEN ATTRACTIVE

Figure 3 shows the price difference between renewable energy levelized cost of electricity, LCOE, technologies and the fossil fuel cost range between 2010 and 2023. The prices for the projects in 2022 and 2023 are auctioned but still must be built. It is shown that, in the most optimal locations, solar PV and onshore wind already have lower LCOE prices from 2018/2019 onwards. This indicates that it is attractive to use these renewable energy resources instead of fossil fuels for electricity generation. The rapid decline in renewable energy prices is the main reason for the interest in green hydrogen production [64][98].

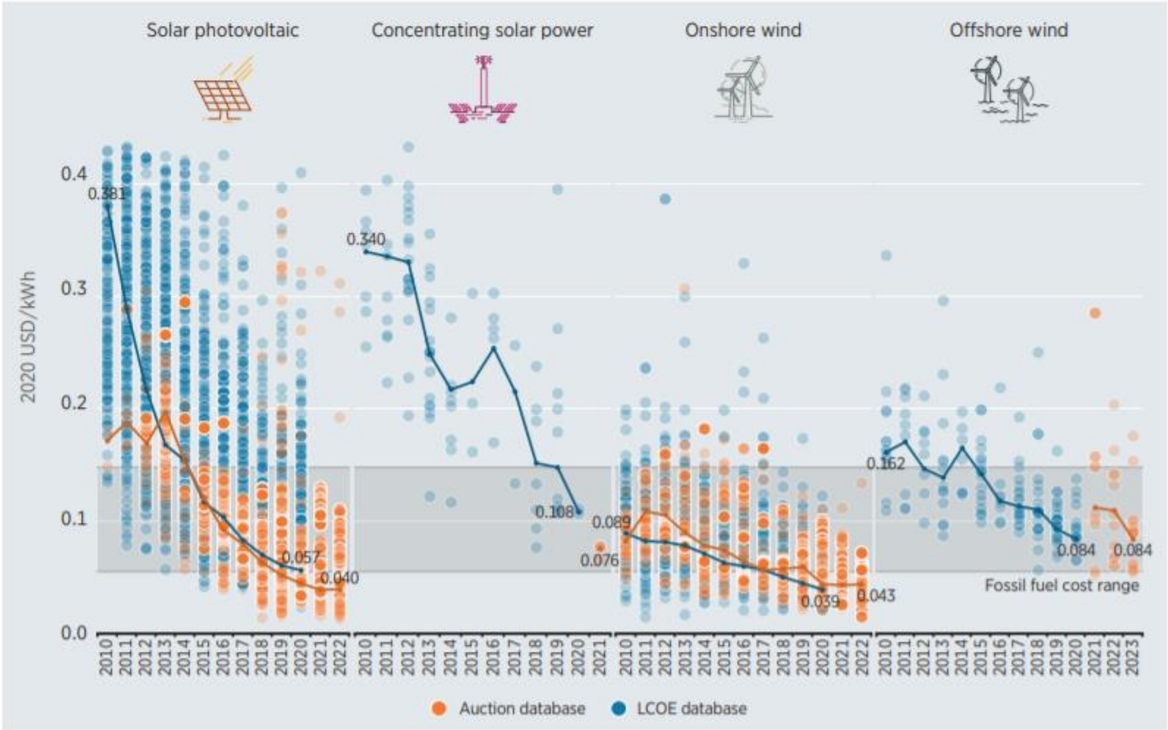


**Figure 3 Projected and global weighted-average LCOE and Power Purchase Agreement/auction prices for solar PV, onshore wind, offshore wind, and Concentrated Solar Power, 2010 – 2023. In addition, the fossil fuel cost range is shown as a comparison. Prices for projects in 2022 and 2023 are auctioned but still must be built [64].**

The energy consumption in Europe is mainly used for heating, mobility, electricity and in the industry for feedstock and high-temperature heating. These sectors consume most fossil fuels produced in Europe. The total energy consumption (Gross Available Energy) of the European Union in 2019 was 1,719 Mtoe or around 20,000 TWh [62]. Hydrogen is a clean-burning gas that can replace the use of coal, oil, and gas in many applications. These energy uses are found in the following sectors.

- Industry (feedstock and high temperature heating processes)
- Buildings & housing (heating and cooling)
- Mobility (road vehicles, ships, planes, and trains)
- Electricity (balancing the electricity demand and supply) [10]

Figure 4 shows how integration of large-scale renewable energy systems to produce hydrogen can decarbonize end uses.

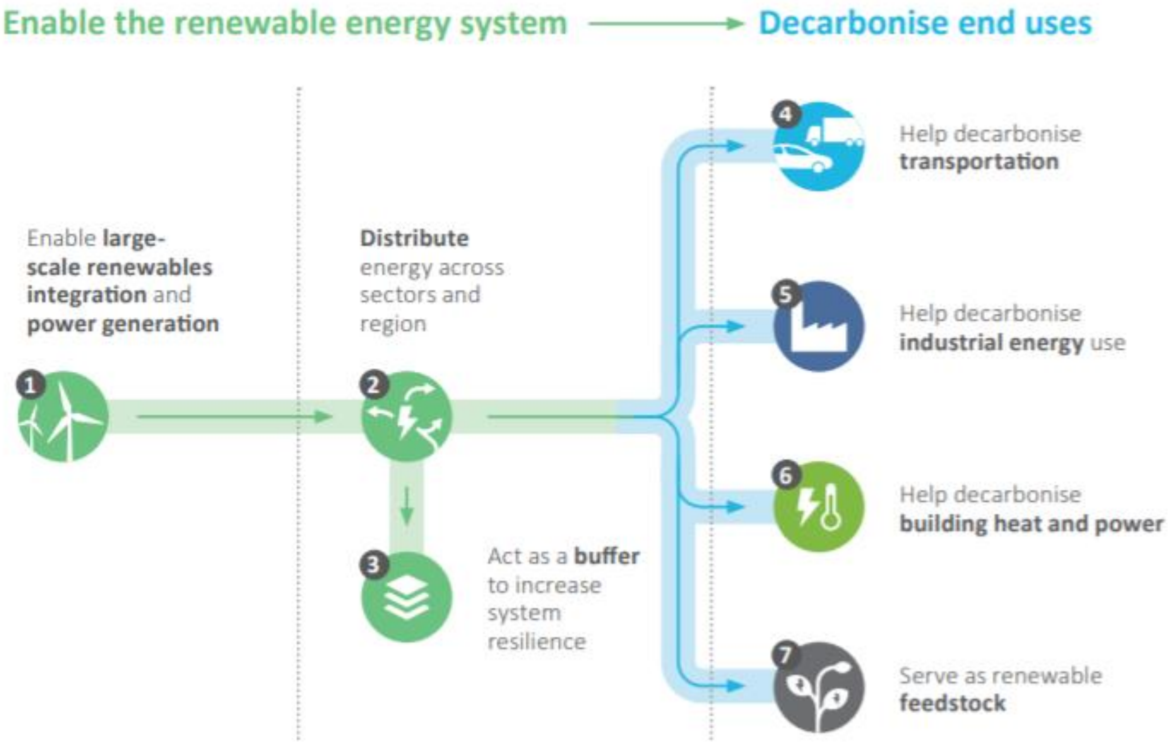


**Figure 4 Enabling renewable energy to produce hydrogen and decarbonize the end-uses. This figures presents a general overview of the roles of hydrogen in decarbonizing the energy system and end-uses [62]**

Hydrogen today is only used in the industry sector. It is expected that the current demand for hydrogen will grow [10]. Petroleum refining companies use hydrogen for hydrotreating and hydrocracking processes. Hydrotreatment is one of the many stages of diesel refining and hydrocracking is the transformation of long and unsaturated products into products with a lower molecular weight than the feedstock. The demand for hydrogen in oil refineries and petrochemical industry in 2018 was 3.7 million tons (148 $TWh_{HHV}$).

Next to oil refineries, hydrogen is used to produce ammonia. The process uses a synthesis of nitrogen with hydrogen, around 180 kg of hydrogen is needed per ton of ammonia. The total demand for hydrogen for this process was 2.8 million tons(112 $TWh_{HHV}$) in 2018.

Lastly, the chemical industry requires hydrogen as a feedstock to produce several chemical products such as hydrogen peroxide, which is used as a disinfectant.
The total demand of hydrogen in 2018 (excluding ammonia production) from the chemical industry is 1.0 million tons(40.8 $TWh_{HHV}$).

Together, the chemical industries and oil refining take up around 93% of the total hydrogen demand. The other 7% of the demand comes from steel manufacturing and metals processing, glass manufacturing, food processing, energy sector and transportation.

In addition, there are new possibilities for the use of hydrogen as a feedstock. In the steel industry hydrogen can replace the function of coal to reduce iron ore [5]. It can also be used to produce synthetic fuels with $CO_2$ such as methanol and kerosine. Also, hydrogen can be used to replace natural gas and coal in process where high temperature heat and steam are needed. In figure 5 the hydrogen demand in the industry sector in 2018 is shown.

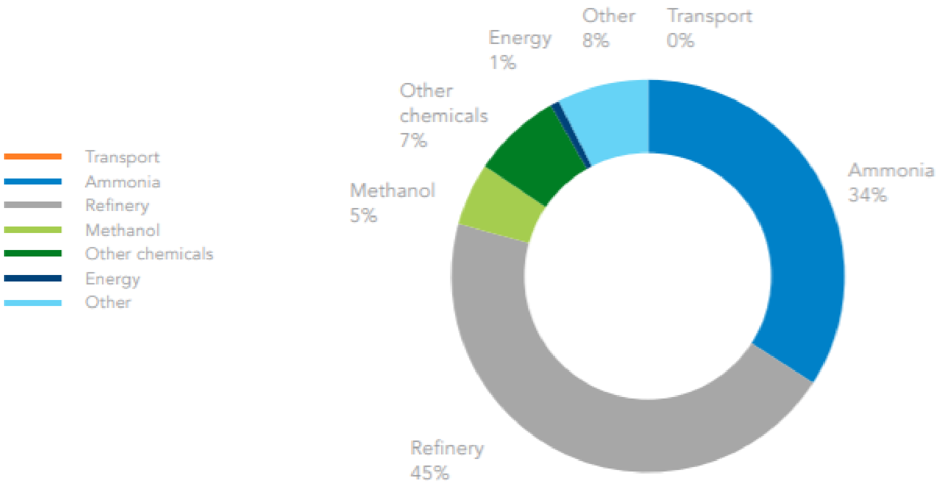


**Figure 5 Hydrogen demand for the industry sector in 2018. The majority of the hydrogen demand stems from refineries and production of ammonia. Hydrogen is used as replacement for heating elements in the production process. [62]**

By 2030 fuel cell electric vehicles could account for 3.7 million passenger vehicles and 500.00 fuel cell light commercial vehicles. In addition, around 570 diesel trains could be replaced by fuel cell trains and 45.000 fuel cell trucks and busses could be operational by 2030. Fuel cells will become a dominant technology, where hydrogen is chemically converted into electricity as fuel for the electric motor in a vehicle [62].

Buildings and housing can use hydrogen for the heating demand by producing heat in hydrogen boilers and hydrogen-ready boilers [10]. Hydrogen is estimated to replace around 7% of natural gas in 2030 by volume and around 32% in 2040. This is the same as that 5 mid-size cities, of around 300.000 inhabitants, which switch to pure hydrogen. This amount of hydrogen can sustain demand of around 2.5 million and 11 million household in 2030 & 2040. In addition, fuel cell CHP's (Combined Heat and Power) installations could take around 15 TWh of power from the grid and increase the energy efficiency by 2040 [62].

Lastly, hydrogen can be used as a power-generation method to balance the electricity grid. This long-term energy carrier can be stored and transported easily and at a low price. Therefore, hydrogen is a suitable method of balancing supply and demand in location and time. In the future, fuel cells could be used to balance out the electricity grid [10].

In figure 6 the future hydrogen demand of the four high-demand sectors is shown for two scenarios.

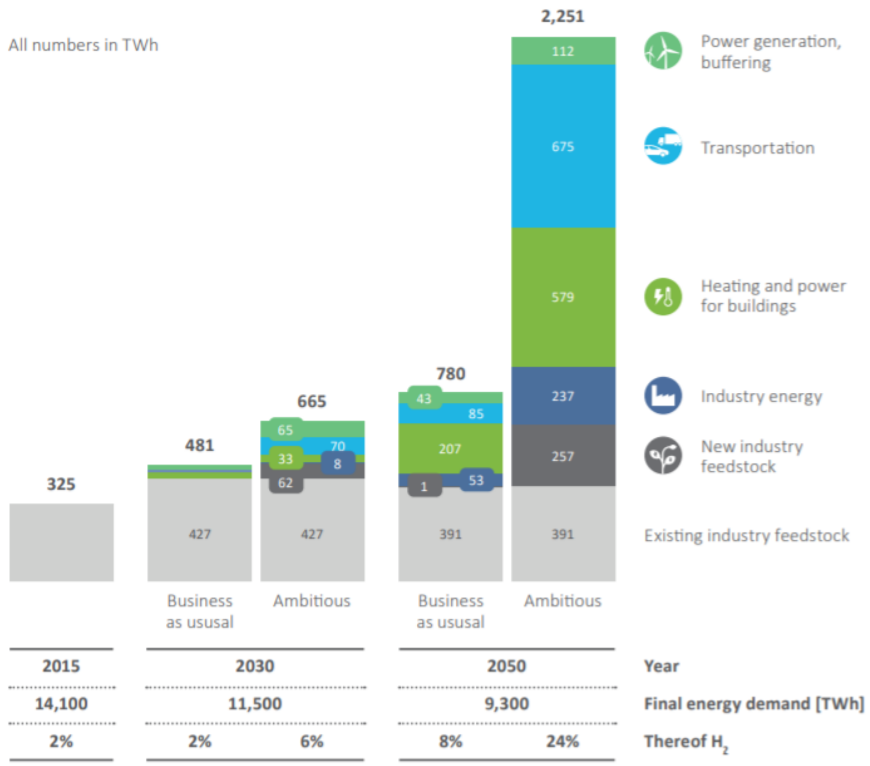


**Figure 6 Future demand of hydrogen in power generation, transportation, buildings, and industry feedstock in 2030 & 2050 for a 'business as usual' and 'ambitious' scenario. It is estimated that hydrogen can supply around 24% of the Europe's total energy demand in 2050. [62]**

In figure 7 the benefits of the use of hydrogen in 2050 for the European Union are shown. In the most ambitious scenario around 24% of the final energy demand in 2050 could come from hydrogen and around 15% of local emissions ($NO_x$) are reduced relative to road transport [62].

**Figure 7 Benefits of large-scale hydrogen for the EU in 2050. Implementing (green) hydrogen into the Europe's energy system has a number of beneficial results. The amount of CO2 emitted is reduced, it returns a high annual revenue, and it leads to more available jobs [62].**

In addition, to build a European energy system consisting of 50% of renewable energy and 50% green hydrogen can be achieved by 2050. The green hydrogen will be produced in Europe and partly imported from North-African countries, which is beneficial for both regions. This approach makes optimized use of (existing) gas infrastructure, which is low in risk, has low costs, it improves Europe's energy security, and it provides development in the European technology leadership. North Africa will benefit as it fosters general economic growth within the region [63].

## EUROPE

The renewable energy resources are good in Europe. But these resources are not evenly distributed throughout Europe so pan-European transport and storage is required for optimal distribution between optimal and less optimal resource regions.

Looking at figure 8 the solar resource potential in Europe is shown. Large-scale solar PV can be built at a low price and subsidy-free in areas with high solar irradiation such as in most South-European countries. Spain, and Portugal show to be good starting points for large-scale solar farms.

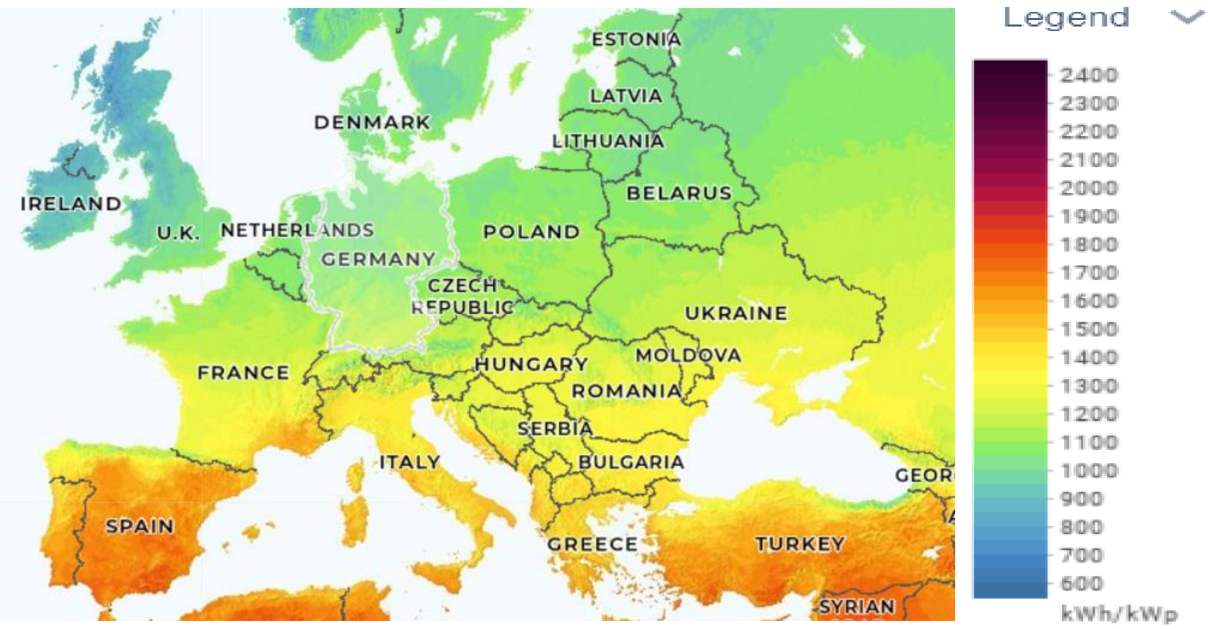


Figure 8 Solar PV potential power output in Europe (kWh/kWp) [15]

In figure 9 the mean windspeeds in Europe are shown at 150m height. The windspeeds in the countries around the North-Sea, Baltic Sea, Irish Sea, and several parts of the Mediterranean Sea show strong potential for onshore wind power production. Large scale onshore wind can be produced at relatively low costs and subsidy-free prices in these parts of Europe [25].

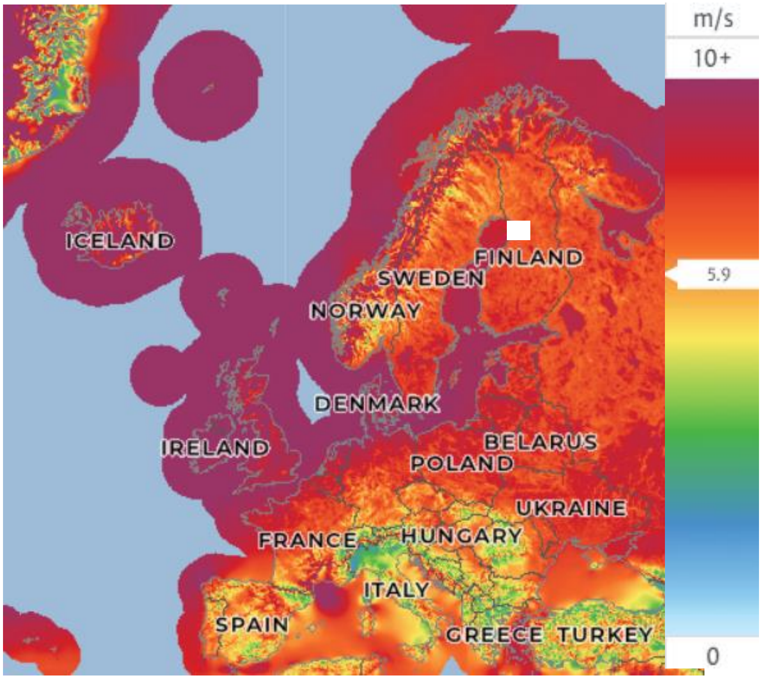


**Figure 9 Mean windspeeds in Europe (m/s) at 150m height. The highest mean windspeeds are mostly located in North-Europe at most coastal areas in Europe. [25]**

## NORTH AFRICA

In the North Africa the renewable resources are excellent. The solar irradiation is even better and more abundant than in Europe. The Sahara Desert provides enough space and is one of the sunniest places on Earth. With locations providing around 2000 load hours of sun per year and a size of 9.4 million km$^2$ it is twice the size of Europe and can provide the world of its energy demand by using around 8-10% of its area [99]. The solar power potential output of North-Africa is shown in figure 10. North Africa is located close to the tropics, where there is almost no clouding, resulting in a high solar power output potential [15].

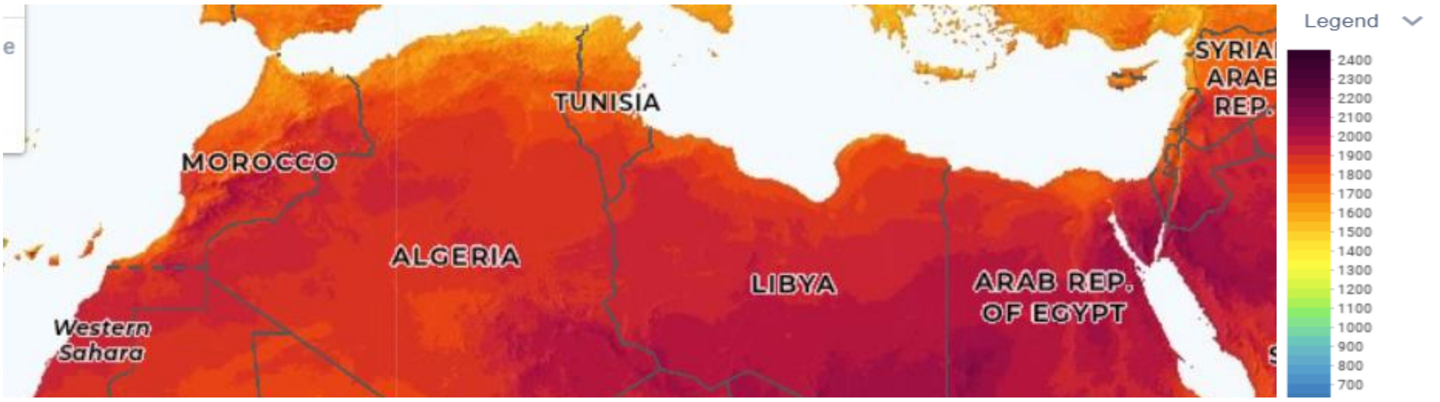


**Figure 10 Solar power potential of North-Africa (kWh/kWp). These areas are close to the equator which automatically means that these areas have a high solar power output potential [15]**

In addition, the North African region is also home to extremely windy places and especially on the West coast of North Africa. Mean windspeeds at ground level are around 5 m/s and for 150m height the mean windspeed is around 10-12 m/s at the West coast. This is more than enough to power large wind turbines with hub-heights at 150m and higher. North African countries such as Algeria, Tunisia and Egypt have windspeeds comparable to North-European regions such as the North-Sea and the Baltic-Sea. The mean windspeeds of North Africa are shown in figure 11 [25].

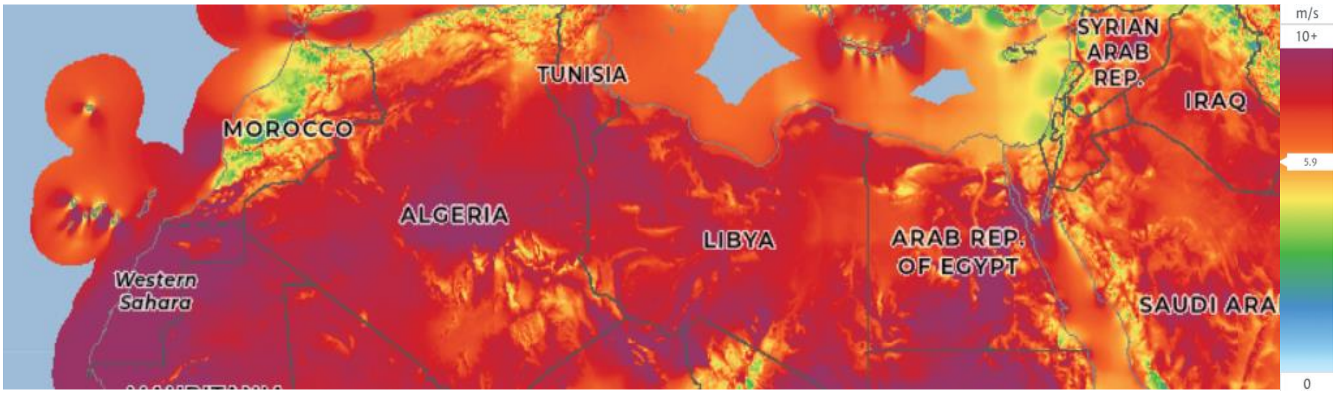


Figure 11 Mean windspeeds in North-Africa at 150m height. The highest mean windspeeds are spread out through North-Africa. [25]

This indicates that North Africa has more than enough resource potential for renewable electricity generation. Also, regions such as the Middle East have good solar and wind resources and therefore have potential to become large green hydrogen producers in the future, as can be seen in figure 11.

## THE GEOGRAPHICAL MISMATCH BETWEEN SUPPLY AND DEMAND

Europe is expected to be a large demand hub for green hydrogen due to limited space, lack of sufficient renewable resources, and high population density [7]. Looking at regions where green hydrogen van be produced very cheaply e.g., the Mediterranean region it is seen that there is a geographical supply and demand mismatch. The hydrogen demand hubs are estimated to be concentrated in Europe, North America, Japan, and China according to figure 12.

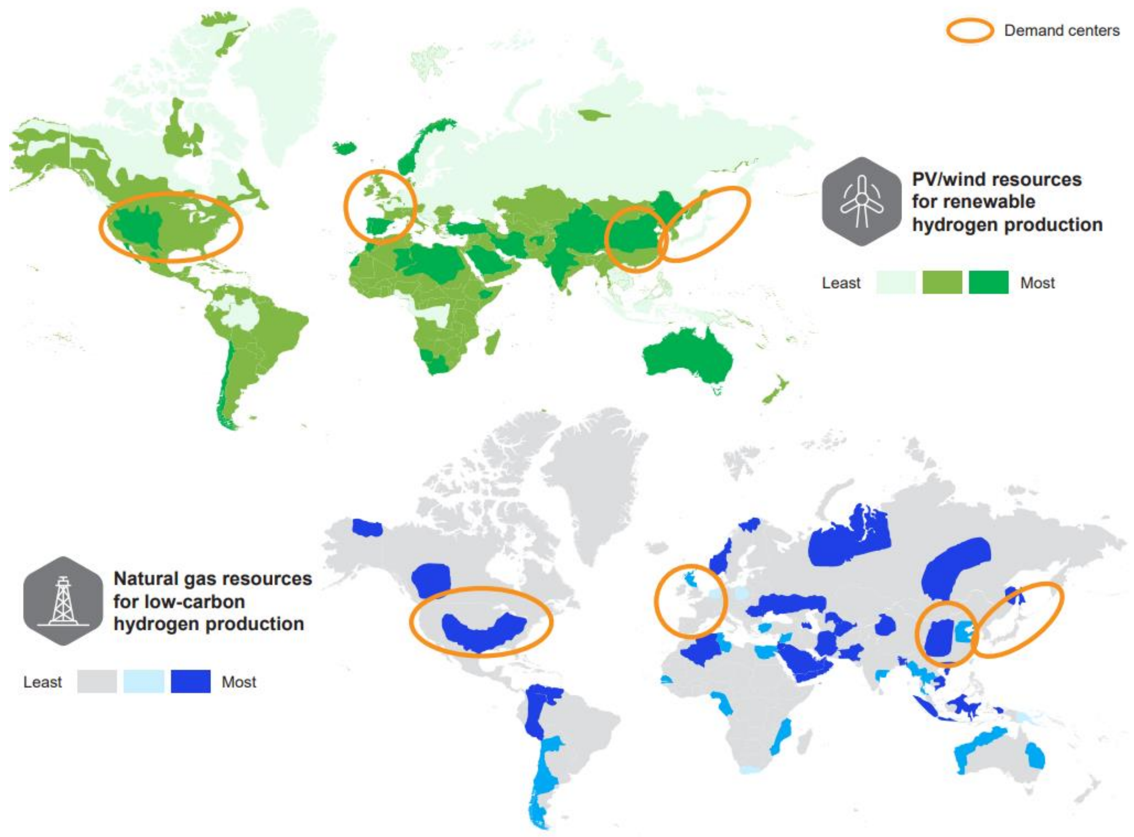


Figure 12 Hydrogen demand centers are located in North America, Europe, Japan, and China [7]

Countries such as Mauritania have an abundance of space and low population density with excellent solar and wind resources. This country can produce enough renewable electricity for hydrogen production to supply its own energy consumption and to export hydrogen to Europe.

Mauritania has a total size of 1.030.000 km$^2$ and an inhabitant count of 4,526 million people. In May 2021, CWP Global, a renewable energy development company, signed a memorandum of understanding for a green hydrogen project with Mauritania for around $40 billion. CWP Global has set out to install a solar and wind to hydrogen system in the North of Mauritania, covering around 8500 km$^2$, which is less than 1% of the total area size of Mauritania, this is shown in figure 13 This project will consist of 30 GW of solar and wind energy to power electrolysers for green hydrogen production. This is enough to produce around 3 million tons of green hydrogen per year

[69]. Figure 13 shows that North-Mauritania has the best solar and wind conditions of the country and even in the world [15][25]. This indicates that this area contains the cheapest clean energy in world, which makes it ideal for low-cost large-scale green hydrogen production systems.

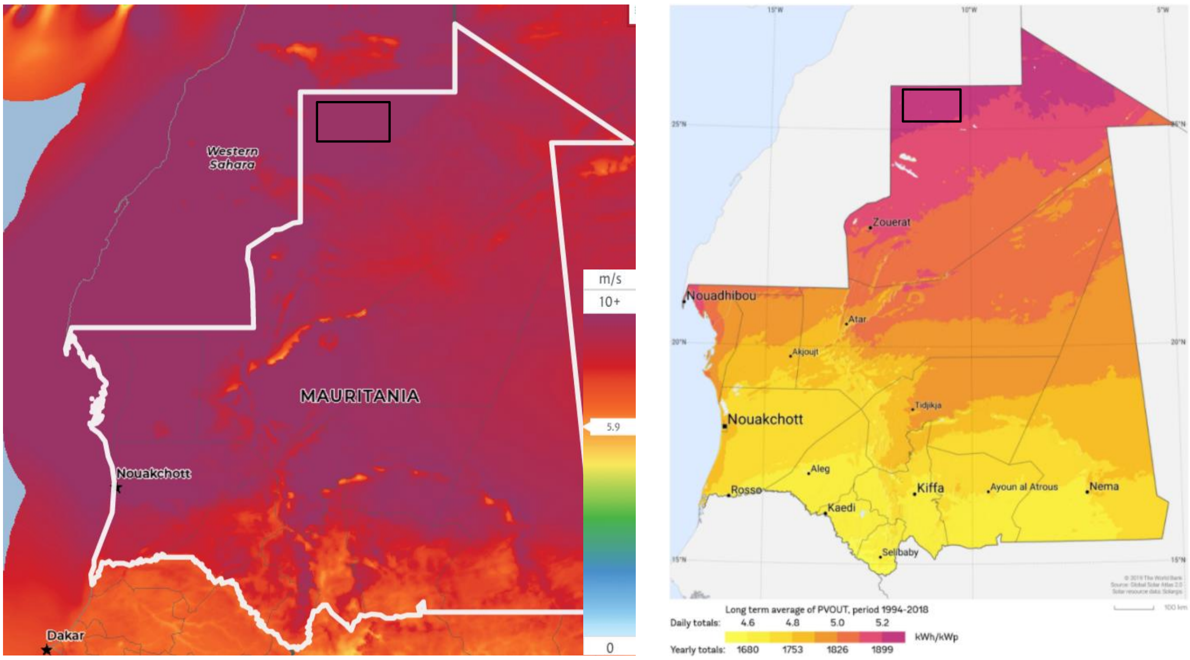


**Figure 13 North-Mauritania shows the best solar and wind conditions in the country and even in the world. Indicating cheap clean energy production [15][25]**

The electricity consumption of Mauritania is around 882 GWh/year [70], which is around 0.02 million tons of hydrogen. This means that around 3 million tons of hydrogen can be used for other domestic energy consumption or for export. In addition, when using the other available space for hydrogen production means that hydrogen production can be up scaled and produced against lower prices than in Europe. Germany is already looking at possibilities to secure new hydrogen supply, and particularly looking at North Africa [63]. Therefore, a hydrogen infrastructure must be built to transport hydrogen from low-priced green hydrogen production areas to the demand regions e.g., Europe.

## 1.2.2. HYDROGEN PRODUCTION

### ELECTROLYZER TECHNOLOGY

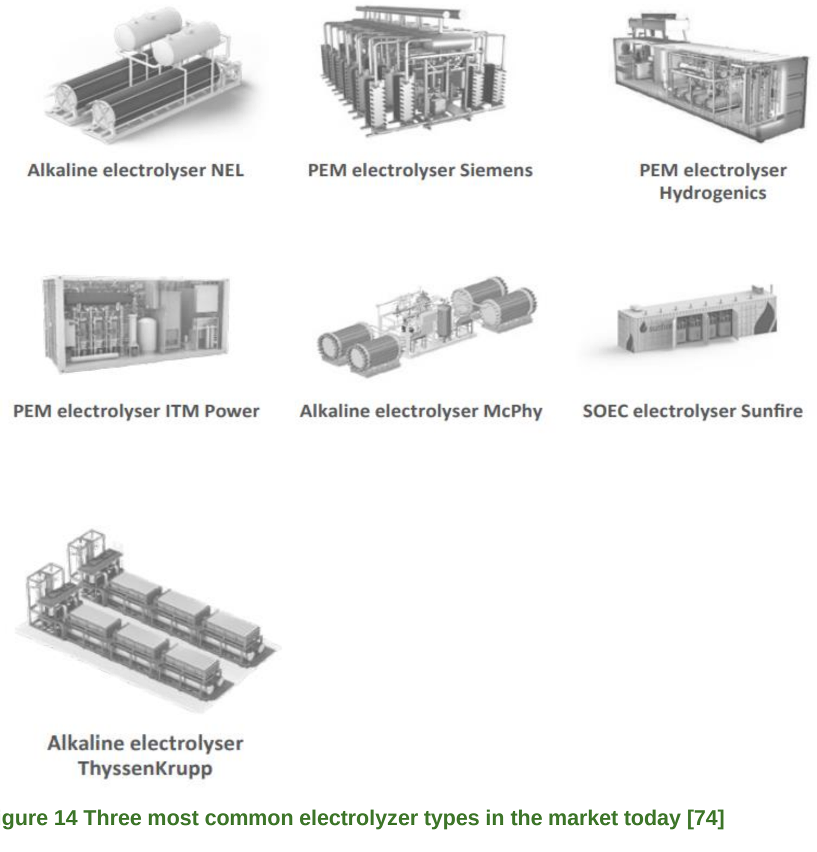
Hydrogen can be produced in many ways. Table 1 shows the different methods of producing hydrogen, maturity of the technology, and indicates what technology is used per source and what 'type' of hydrogen comes from that process. Green hydrogen comes from biogas, biomass, and electrolysis from water with renewable energy. Europe is a front runner in the electrolyzer market and has a significant market position [10].

**Table 1 Hydrogen color with source, maturity, and technology. Alkaline electrolysers are the only electrolysis technology that is mature to this date.**

| **Source** | **Process/Technology** | **Maturity** | **Colour of Hydrogen** |
|---|---|---|---|
| **Natural gas** | Steam methane reforming<br>Auto-thermal reforming<br>Thermal Pyrolysis | Mature<br>Mature<br>First plant 2025 | **Grey [71]** or **blue [71]**,<br>depending on the CCS technology 50-90% of CO2 can be captured and stored. With ATR higher CO$_2$ emission reductions with lower cost are possible<br>**Turquoise [71]**, CO$_2$ emissions<br>Depend on the source for electricity production |
| **Coal** | Partial Oxidation/Gasification<br>Underground coal gasification | Mature<br>Projects exist | **Brown[72]** or **blue[71]**,<br>depending on the CCS technology 50-90% of CO$_2$ can be captured and stored. |
| **Solid Biomass, Biogenic waste** | Gasification<br>Plasma gasification | Near Maturity<br>First Plant 2023 | **Green [71]**<br>Negative CO$_2$ emissions possible |
| **Wet Biomass, Biogenic waste** | Super critical water gasification<br>Microbial Electrolysis Cell | First Plant 2023<br>Laboratory | **Green [71]**<br>Negative CO$_2$ emissions possible |

| | | | |
|---|---|---|---|
| **Electricity + Water** | Electrolysis<br>Alkaline<br>PEM<br>SOEC | <br>Mature [26]<br>Near Maturity [26]<br>Pilot Plants [26] | All shades of **grey** to **green** depending on the source for electricity production **[71]** |
| **Sunlight + Water** | Photoelectrochemical | Laboratory | **Green [71]** |

In addition, there is more and more hydrogen production via water electrolysis happening today as there are more initiatives to produce green hydrogen in the future [73]. Electrolyzer technology is not uncommon in Europe as most of the electrolysers are European technology. Green hydrogen provides around 0.02% of global pure hydrogen production in 2020 through water electrolysis [10]. Figure 14 shows the three main types of electrolysers used for water electrolysis: PEM (Proton exchange Membrane), alkaline and solid oxide (SOEC). The three electrolysers function somewhat differently, depending on the electrolyte material used in the electrolyzer. Alkaline and PEM can both deliver on-site and on-demand (green), pressurized without a compressor, pure (99.999%), and dry hydrogen [74].



Alkaline electrolyser NEL

PEM electrolyser Siemens

PEM electrolyser Hydrogenics

PEM electrolyser ITM Power

Alkaline electrolyser McPhy

SOEC electrolyser Sunfire

Alkaline electrolyser ThyssenKrupp

Figure 14 Three most common electrolyzer types in the market today [74]

Most projects are in megawatt-scale and despite this the technology is commercial and ready to upscale in the future. Around 25 GW of projects have been announced for between 2020 – 2025 and even more are being planned for in the future, as mentioned in table 1. Figure 15 shows the different learning rates of the electrolysis technology, only includes stack and balance of plant, between 2020 and 2030. The learning rates vary between 12 – 20 %, which indicate three scenarios of cost future cost reductions of this technology [7]. Due to the upscaling and innovation of this technology in the future will decrease the costs of this technology and increase the technology efficiency. Especially mass production of cells and stacks and integration with renewable energy technology will lead to cost reductions [26].

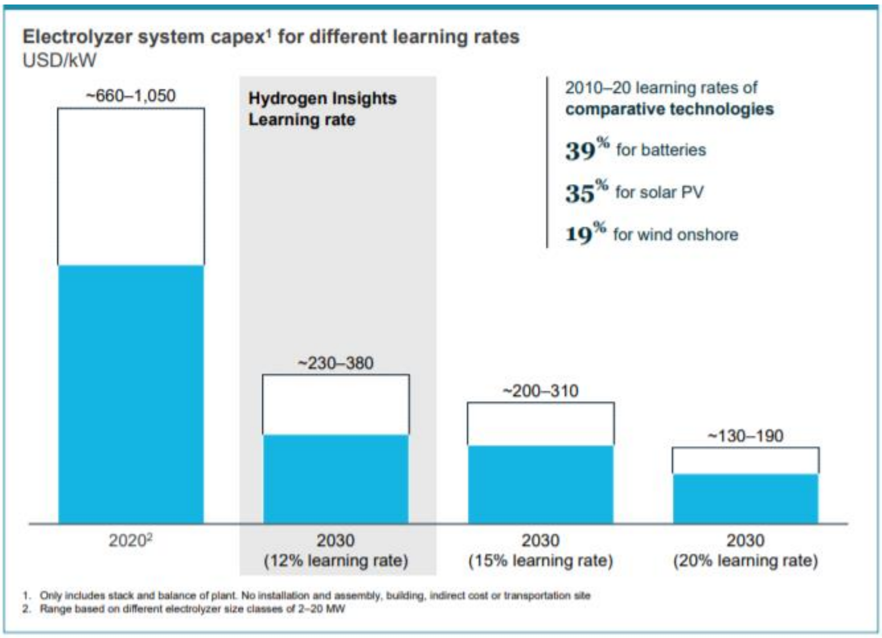
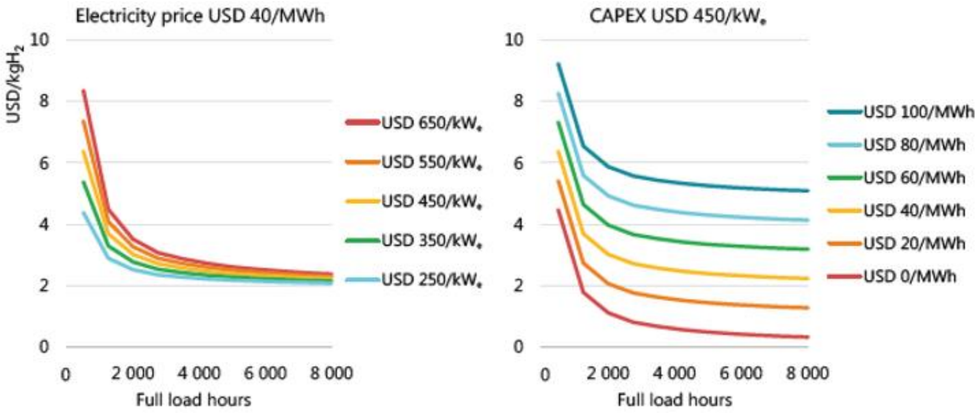


**Figure 15 Different electrolysis technologies and production costs by electrolysers from 2020 up to 2050, showing capex, opex, system efficiency (HHV), electricity, and hydrogen production price**

Figure 16 shows the future levelized cost for alkaline and PEM electrolysers by operating hours for different investment costs and electricity prices. More full load hours mean the technology can produce green hydrogen at lower prices. It can be seen in figure 16 that when full load hours increase the effect of capex on the production price decreases but the and the impact of electricity prices increases. Therefore, low-cost electricity is essential for low hydrogen production costs [5].



Notes: MWh = megawatt hour. Based on an electrolyser efficiency of 69% (LHV) and a discount rate of 8%.

Source: IEA 2019. All rights reserved.

**Figure 16 Future levelized cost of hydrogen production by operating hour for different electrolyzer electricity costs (right) and investment costs (left) [5]**

### 1.2.3. HYDROGEN TRANSPORT

The volumetric density of hydrogen is about a factor 3 lower than the volumetric density for methane, see table 2. The low volumetric density of hydrogen makes it more expensive to transport this gas by road or ship than methane. But hydrogen can travel 3 times as fast as methane through pipelines, without causing turbulence in the pipeline. Hydrogen has a lower boiling point than methane, which indicates that compression is needed for the transport of hydrogen.

**Table 2 Properties of hydrogen vs. methane for transport. Hydrogen has a lower volumetric energy density than methane but is almost 3.5 times lighter than methane**

| **Property** | **Unit** | **Hydrogen** | **Methane** |
|---|---|---|---|
| *Boiling point* | °C at 1 bar | -252.76 [113] | -161.6 [9] |
| *Mass Energy density* | MJ/kg (HHV)<br>MJ/kg (LHV) | 141.8 [10]<br>120.0 [113] | 55.5 [11]<br>50.0 [11] |
| *Volume Energy density (25 C, 1 bar)* | MJ/m$^3$ (HHV)<br>MJ/m$^3$ (LHV) | 11.54 [113]<br>9.76 [113] | 36.46 [115]<br>32.85 [115] |
| *Buoyancy* | Relative to Air | 14.5 x lighter [114] | 4 x lighter (natural gas) [114] |

Considering the chemical characteristics of hydrogen and looking at table 2 it can be said that hydrogen transport by pipeline is the most cost-effective method for long/short distance transport. This shown in figure 17. It shows that there are three effective methods to transport hydrogen, by pipeline/ship/truck, in four different forms, compressed $H_2$/Liquid $H_2$/Ammonia/Liquid Organic Hydrogen Carriers. For transport up to 5000km using pipelines is the cheapest option, which is good for using for pan-European transport of hydrogen. Above 5000km ships are the best option due to lack of infrastructure between far-away continents such as North America and Africa. Trucks are used when small volumes of hydrogen, between 1-10 tons/day, are needed for locations that are not nearby pipelines [106]. The downside of this method is the increase in costs per distance when travelling further than 100km. Figure 17 is used as an example to depict the possible means of hydrogen transport. This study overestimates the costs of hydrogen transport through pipelines (0.58 €/kg). This means that for this research the costs shown in figure 20 are considered.

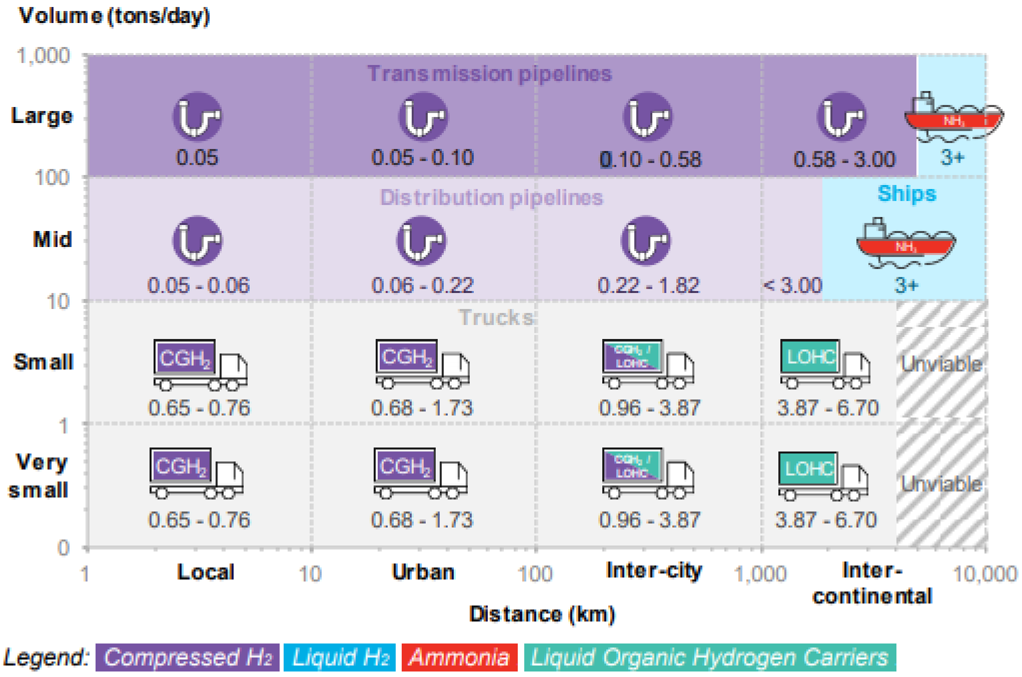


Figure 17 Hydrogen transport costs based on distance and volume in $/kg in 2019. These costs include the cost of movement, compression, and associated storage (this is 20% for pipelines in a salt cavern). Ammonia is assumed non-suitable for small scale due to its toxicity. $LH_2$ is expected to be commercially more used in the future instead of LOHC, even though LOHC is cheaper to transport by trucking over long distances [106]. This study overestimates the costs for transport through pipelines (0.58 €/kg), but in reality, the costs are lower.

The transmission pipelines serve to carry gas from supplier to industrial consumers and distribution networks by large-diameter and high-pressure steel pipes. The average pipeline is between 16-56 inches, operators between 16-100 bar pressure and medium to large size pipelines can transport between 9-17 GW of hydrogen. To use the existing pipeline infrastructure, it first must be retrofitted to accommodate for the specifications of hydrogen. Research from the first hydrogen projects by European gas TSOs show that hydrogen pipelines don't significantly differ that much from natural gas pipelines. Therefore, retrofitting these pipelines can be done quickly and easily at a low cost. These TSOs have researched that building a new hydrogen pipeline system will cost between 10-50% more capital than its natural gas counterpart. In addition, retrofitting existing natural gas pipelines will cost between 10-25% of the capital needed to build a new hydrogen pipeline infrastructure. However, potential from the Baltic Sea and Greece still must be unlocked and therefore a new hydrogen pipeline system is needed to connect these regions [81][83].

Countries such as The Netherlands and Germany have already started implementing hydrogen pipelines by converting natural gas pipelines, shown in figure 18. This shows that hydrogen supply from regions in and around these two countries can now be connected to the industrial demand and storage facilities such as salt caverns. These proposed networks in figure 18 all consider the locations of large industries and chemical facilities, as well as suitable and cheap salt cavern storage possibilities [10][100].

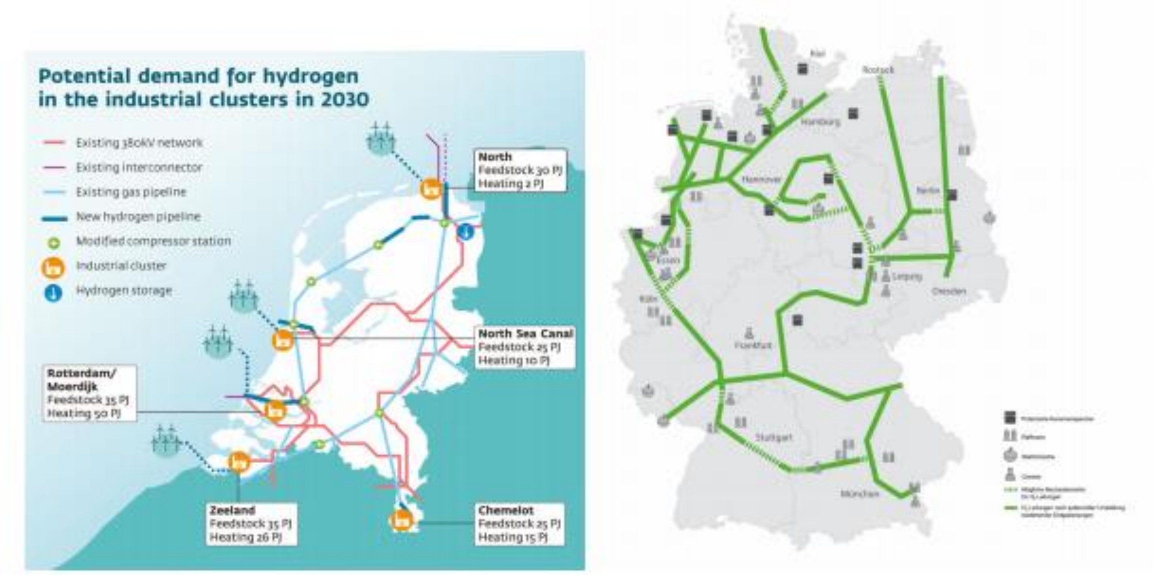


Figure 18 Hydrogen infrastructure The Netherland and Germany. Existing natural gas pipelines are converted to hydrogen transport pipelines, which connect the hydrogen supply to the storage and demand [100].

In figure 19 the proposed European hydrogen backbone is depicted. It has a total length of 40.000 km across 21 European countries with highly diverse gas infrastructure. Around 69% of existing natural gas pipelines is retrofitted, the other 31% is new hydrogen pipelines. This proposed infrastructure should be able to transport the 1130 TWh of annual hydrogen demand by 2040 in Europe [83].

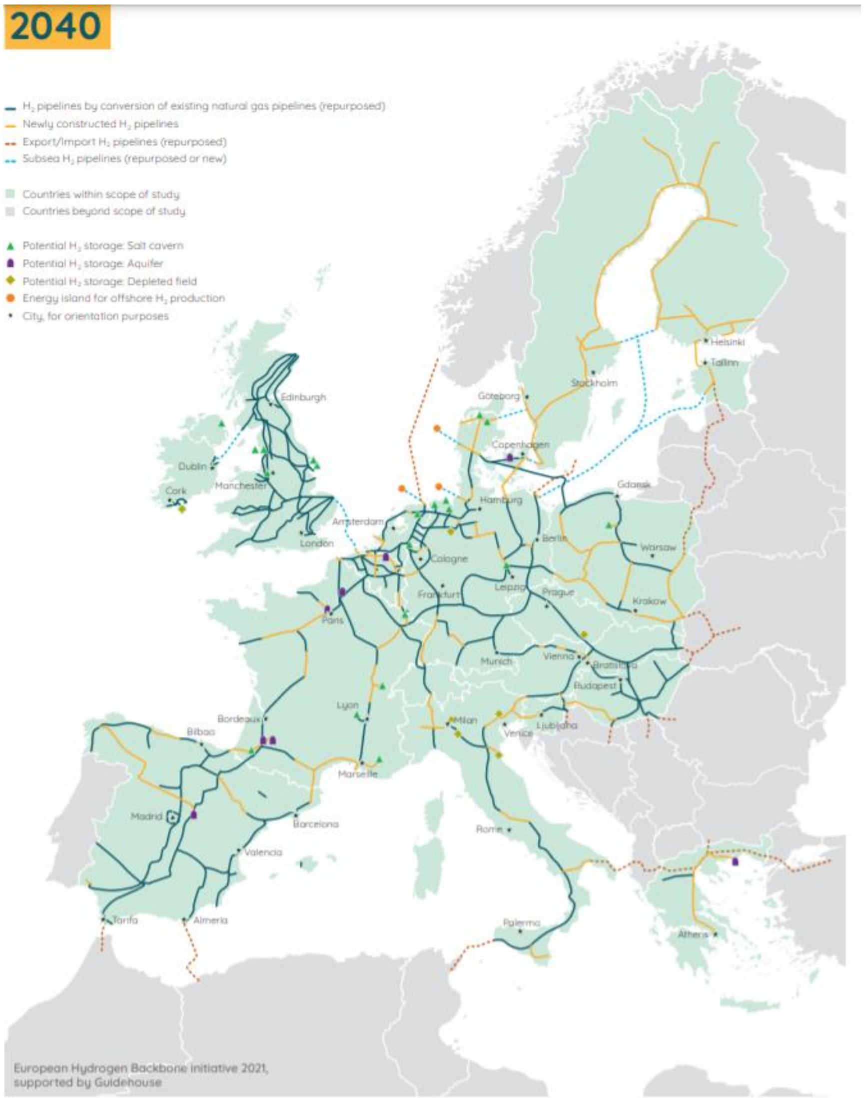
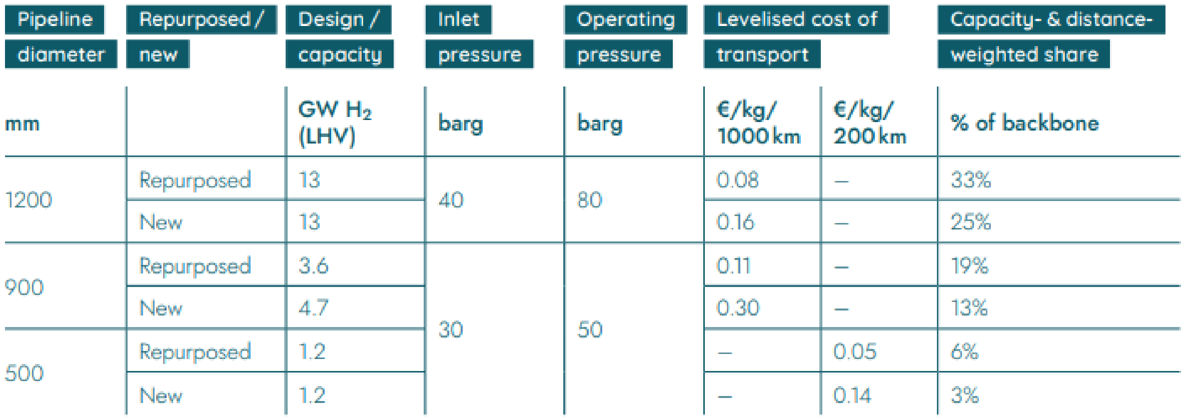


**Figure 19 Proposed European hydrogen backbone in 2040. This hydrogen backbone allows for pan-European transport and forms a bridge between North-Africa and Europe. [83]**

By 2040, the natural gas demand is expected to reduce to 50% of the demand in 2020. Around 2030 the pipeline infrastructure of figure 20 is expected to only connect hydrogen producers to industrial demand. It is expected that in 2040 more sectors such as power and transport will become significant hydrogen consumers and with this infrastructure large amounts of hydrogen will be able to fill this demand [81][83].

In figure 20 the levelized cost of new-, 100% & 75 % retrofitted infrastructure for three input scenarios is shown. The scenarios differ on basis of pipeline capex, compressor capex, electricity price, depreciations of pipelines and compressors, weighted average cost of capital, and O&M costs.



| Pipeline diameter | Repurposed / new | Design / capacity | Inlet pressure | Operating pressure | Levelised cost of transport | | Capacity- & distance-weighted share |
|---|---|---|---|---|---|---|---|
| mm | | GW $H_2$ (LHV) | barg | barg | €/kg/ 1000 km | €/kg/ 200 km | % of backbone |
| 1200 | Repurposed | 13 | 40 | 80 | 0.08 | – | 33% |
| | New | 13 | | | 0.16 | – | 25% |
| 900 | Repurposed | 3.6 | 30 | 50 | 0.11 | – | 19% |
| | New | 4.7 | | | 0.30 | – | 13% |
| 500 | Repurposed | 1.2 | | | – | 0.05 | 6% |
| | New | 1.2 | | | – | 0.14 | 3% |

**Figure 20 Levelized cost of new- and retrofitted infrastructure in 2040 for a small, medium, and large size pipeline diameter. 900mm is the size considered for this research [83].**

Expecting to build hydrogen pipelines to reach regions such as the Baltic Sea, North Sea and Greece, and having the rest of the pipelines retrofitted, and assuming the high input scenario, the average price of transporting hydrogen is estimated to be 0.16 €/kg/1000km for 5000 load hours [83].

Most of the synthetic fuel production plants and chemical industry are designed to work on baseload. Therefore, baseload hydrogen is crucial. As 5000 load hours is not considered baseload, the price must be converted to the baseload. Calculating the transport cost to baseload, 8,000 hours, the costs of pipeline transport, without storage costs, for hydrogen is estimated to be 0.1 €/kg/1000km [101].

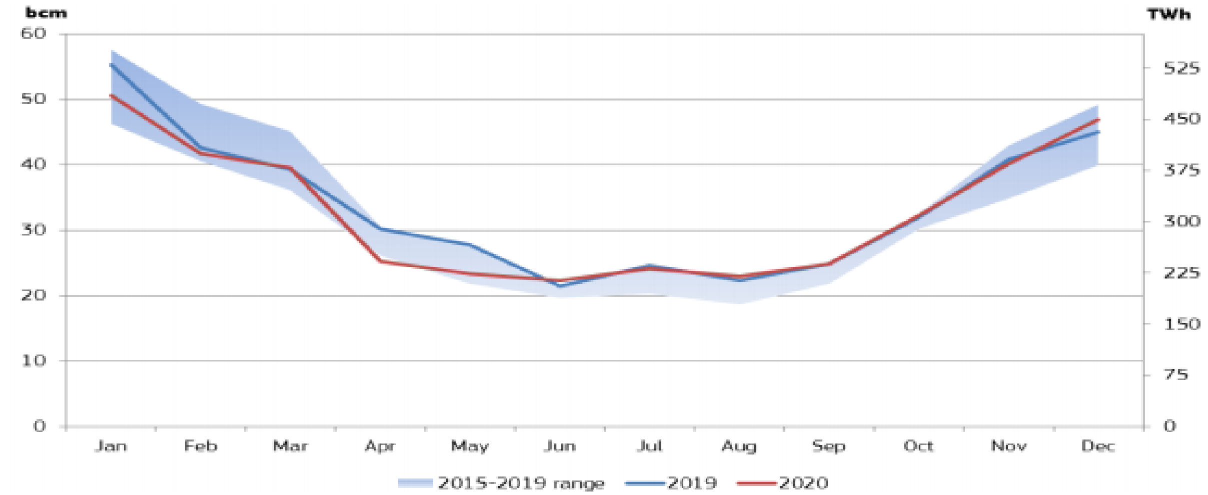
North Africa the solar and wind resources are better and abundant than in Europe. These resources are sufficient to cover the energy demand of these countries and to provide energy to Europe's demand. North Africa exports natural gas via Algeria and Libya by pipelines to Spain and Italy. The energy capacity of these pipelines is more than 60 GW. Also, there are two electricity cables with a capacity of 0.7 GW between Spain and Morocco. This difference between capacities indicates that it is interesting to look at the possibility at unlocking renewable energy export between North Africa and Europe by converting renewable energy into hydrogen and transporting it via this pipeline. In addition, the construction of new hydrogen pipelines is a cheaper option electricity to transport renewable energy from North Africa to Europe [10].

To construct an even bigger hydrogen pipeline, comparable to the Nordstream gas pipeline, from Egypt to Italy, via Greece, of 2500km long, and having a capacity of 66 GW with a width of 48-inch consisting of 2 pipelines, will cost €16.5 billion. With a load factor of 4500 hours, which stems from a combination of solar and wind energy generation, can transport around 7.6 million tons of hydrogen per year. Transport cost will be around 0.2 €/kg $H_2$ or 0.005 €/kWh on HHV over 2,500 km, which is shown in figure 21 [8].

Figure 21 Hydrogen and natural gas pipeline infrastructure plans. The Black/orange pipelines ae converted natural gas pipelines to hydrogen. The orange pipeline from Egypt to Italy is a new pipeline with a capacity of 33 GW. [8]

## 1.2.4. HYDROGEN STORAGE

Storage is needed for fluctuations from seconds to seasonal, in energy demand in Europe . During the winter more energy is used than in summertime, especially for heating and electricity. Gas demands are then 2-3 times higher [101], shown in figure 22.



Source: Eurostat, data as of 10 March 2020 from data series nrg_103m. In the next edition of this report numbers might change retrospectively

**Figure 22 EU monthly gas consumption 2015-2020. During the spring and summer, the least amount of energy is consumed due to the higher average temperature and longer daylight than during autumn and winter. [101]**

Already today natural gas is stored during summer months for use in winter because gas production and supply is in baseload. Also, storage will become important in the future to deal with the intermittent character of electricity production by wind and solar.

Storage plays an important role in the competitiveness of hydrogen and the economic potential of hydrogen comes from that it can be stored relatively cheap in large quantities for long periods of time.

Looking at methods for hydrogen storage there are four alternatives: Geological storage, compressed hydrogen, liquified hydrogen, and materials-based storage [102]. When storing large amounts of hydrogen, which is essential for a continuous operation in the supply chain value, liquid and pressure vessels are not suitable. Aquifers, depleted gas fields and salt caverns are viable options for hydrogen storage but difference between these methods lies in their propriety use with hydrogen. Gas reservoirs and aquifers have difficulties with the permeability of the storage environment and salt caverns are known to be able to store pure hydrogen, as has been done since 1970 in the United Kingdom. Figure 23 shows different hydrogen storage techniques and compares the cycles/year and pressure used with the hydrogen storage cost per technology [104].

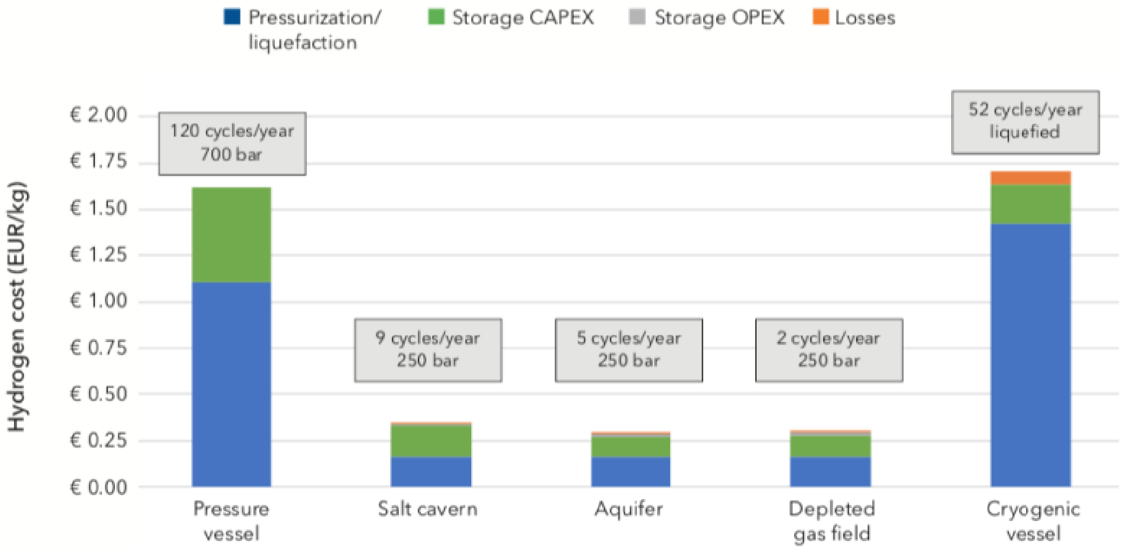


**Figure 23 Storage possibilities for hydrogen. The salt cavern operates at the same pressure as an aquifer and depleted gas field and this graph indicates that it is one of the cheaper options for hydrogen storage possibilities. [104]**

Figure 23 shows that salt caverns are one of the cheapest methods for hydrogen storage when compared to other technologies. In addition, the costs for hydrogen storage in salt caverns is estimated around 0.2 €/kg hydrogen for 5000 load hours [106]. Bringing this to baseload, 8000 load hours, the average costs are estimated at 0.13 €/kg [107]. The average salt cavern can store around 6000 tons of hydrogen, 240 GW, with installation costs (Capex)of around €100 million [105]. When comparing this to battery storage for the same amount of energy it would cost 100 €/kWh and have a total investment of €24 billion. This makes hydrogen storage in salt caverns 100 times cheaper than battery storage [10].

Although depleted gas fields can store up to 10 times more energy than salt caverns the latter is the most suitable for a number of reasons. Salt cavern storage has high efficiencies and low costs in comparison to the other storage techniques. Salt caverns are ideal candidates for hydrogen storage as rock salt is chemically neutral to hydrogen, as the walls are impermeable for hydrogen and the salts plasticity prevents fracture formations [103]. The average salt cavern in Europe is around 680.000 $m^3$ and can have pressures up to 250 bar [104], whereas hydrogen is stored to a maximum of 200 bar for underground geographical storage. In addition, these formations have low construction costs, low leakage rates, and minimal risk of hydrogen contamination [103].

Figure 24 shows all salt formations, salt caverns and salt caverns in use for gas storage in Europe and North Africa. Hydrogen demand centers such as Germany are located close to salt formations and salt caverns, which is beneficial for the overall costs of storage in that region. In addition, low-cost renewable electricity generation countries, e.g., Spain for solar PV and Denmark for wind and North Africa for both, are also located close to these salt formations. This makes large-scale storage in salt caverns more accessible for these regions [10].

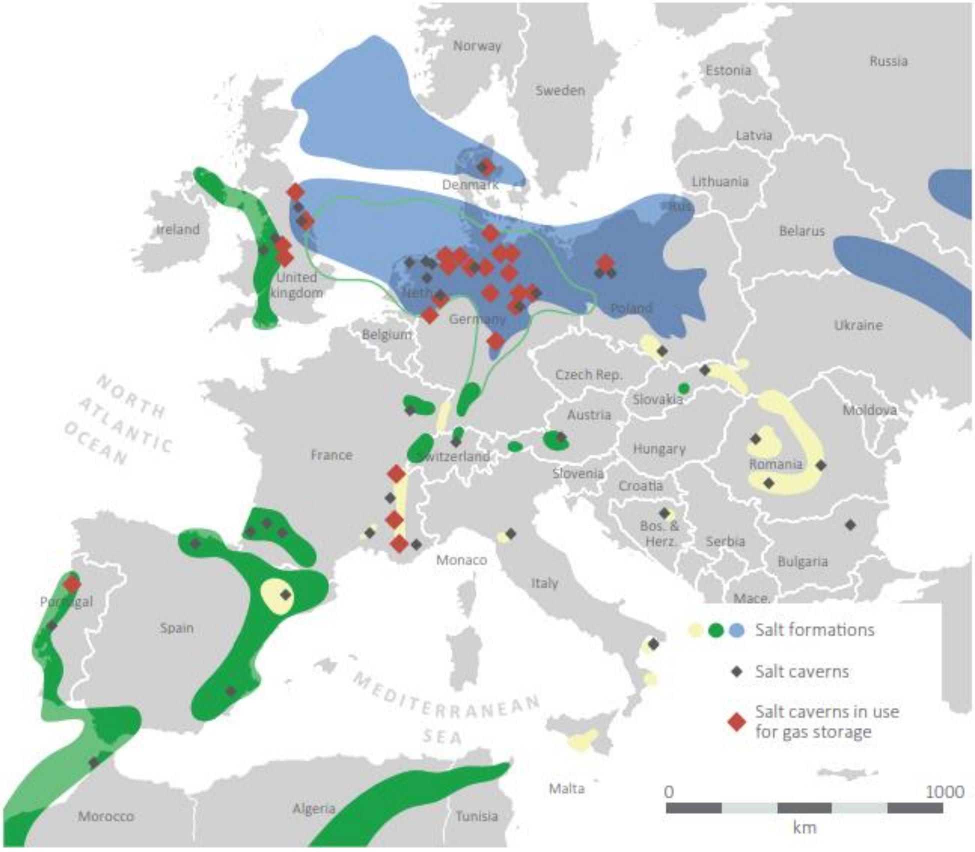


Figure 24 alt formations with available salt caverns in Europe. The red squares are salt caverns already in use for natural gas storage, the grey squares are the salt caverns available, and the green/blue circles are the salt formations [10]

## 1.2.5. POLICY MAKERS AND COMAPANY INVOLVEMENT IN THE HYDROGEN MARKET

### GREEN HYDROGEN INCLUDED IN POLICY MAKING

Today, more and more countries are putting (green) hydrogen into future energy roadmaps. The Hydrogen Initiative was signed by 24 member states in 2018 and several national ministries have joined the European Clean Hydrogen Alliance. Particularly Germany has put emphasis on hydrogen decarbonizing the country in the future. The EU hydrogen strategy developed in 2020 to accelerate green hydrogen development, which must ensure its role as a cornerstone of a climate-neutral energy system by 2050. Hydrogen today only plays a minor role in the European energy system, with challenges in costs, scale of production, infrastructure, and perceived safety [108].

### FUTURE PROJECTS FOR LARGE SCALE GREEN HYDROGEN PRODUCTION

Looking at other initiatives for large scale green hydrogen production, table 3, show that the average amount of production is between 0.5 – 3.5 million tons of hydrogen production. The 10 GW 36-inch medium-sized the pipeline system in Europe can transport around 1 million tons of hydrogen production per year. Larger 48-inch 20 GW pipelines e.g., proposed pipeline infrastructure between North Africa and Europe, can transport around 3 million tons of hydrogen per year [109].

**Table 3 Global large scale green hydrogen projects. The average system size for 1 million tons of green hydrogen per year is around 16GW of renewable energy sources. [109]**

| Project name | Power source & size | $H_2$ output | Date of completion | Use | Location |
|---|---|---|---|---|---|
| HyDeal Ambition | 95 GW of decentralized solar to power 67 GW of electrolysers | 3.6 million tons per year | Before 2030 | Green hydrogen to Europe | Multiple site across Western Europe e.g., Spain, France, and Germany |
| Kazakhstan (unnamed) | 45 GW of wind and solar to power 30 GW of electrolysers | 3 million tons per year | Final investment statemen between 2024-2027 | Export and local use | Kazakhstan |

| | | | | | |
|---|---|---|---|---|---|
| Western Green Energy Hub | 50 GW of wind and solar to power 28 GW of electrolysers | 3.5 million tons per year (20 million tons of ammonia) | Final investment statement after 2028 | Export and local use | Southeast Western Australia |
| Aman | 30 GW of wind and solar to power 20 GW of electrolysers | 3 million tons per year | Not stated | Green steel, long-distance shipping, decarbonizing ammonia fertilizer | Northern Mauritania |
| Oman (unnamed) | 25 GW of solar and wind to power 14 GW of electrolysers | 2 million tons per year | 2038, 1/3 of full capacity in 2028 | Export | Oman |
| Asian Renewable Energy Hub | 16 GW of onshore wind and 10 GW of solar to power 14 GW of electrolysers | 1.75 million tons per year | 2027-2028 | Green hydrogen and green ammonia export to Asia | Western Australia |
| NortH2 | 16 GW of offshore wind to power 10 GW of electrolysers | 1 million tons per year | 2040 | Power heavy industry in The Netherlands and Germany | The Netherlands |
| AquaVentus | Offshore wind for 10 GW of electrolysers | 1 million tons per year | 2035 | Sale via European Hydrogen network | Germany |
| HyEnergy Zero Carbon Hydrogen | Wind and Solar for 8 GW of electrolysers | Around 700.000 tons per year | 2030 | Green hydrogen and green ammonia and later for export to Asia | Western Australia |
| Murchison Renewable Hydrogen Project | Onshore wind and solar for 5 GW of electrolysers | Around 500.000 tons per year | 2028 | Transport fuels, blending in natural gas pipelines and export | Western Australia |
| Beijing Jingneng Inner Mongolia | Onshore wind and solar for 5 GW of electrolysers | 400.000 – 500.000 tons per year | 2021 | Not known | Mongolia |

All these projects are in countries with abundance in space, excellent renewable energy resources and in regions with low population density. This is essential for this scale of hydrogen production. This forms a problem when trying to implement this gigawatt-scale system in densely populated areas with less space and average to good renewable energy resources.

When looking the Asian Renewable Energy Hub project, the area size needed is large. Table 3 shows the amount of space needed for these large-scale projects. With a hydrogen output or around 1.75 million tons the required space is estimated at 6500 $km^2$[110]. This indicates that projects with output of 1 million tons of hydrogen also require large amounts of space for production.

A useful program to determine the space availability for large-scale renewable energy projects is ArcGIS Pro. As renewable energy projects have grown in the last decade, GIS has become an essential ally in identifying locations for geographic solutions for renewable energy production. A spatial analysis reveals the prime areas for renewable energy production by determining the potential of a location based on several criteria [112]. For instance, for a wind farm suitability analysis not only the wind resource is considered but also the slope, off-limit areas, distance to transmission lines, distance to road, and population density can be considered into the program. This gives a more in-depth view on the available amount of area for renewable energy production. Figure 25 shows the process a site suitability model for a wind farm with ArcGIS Pro [111].

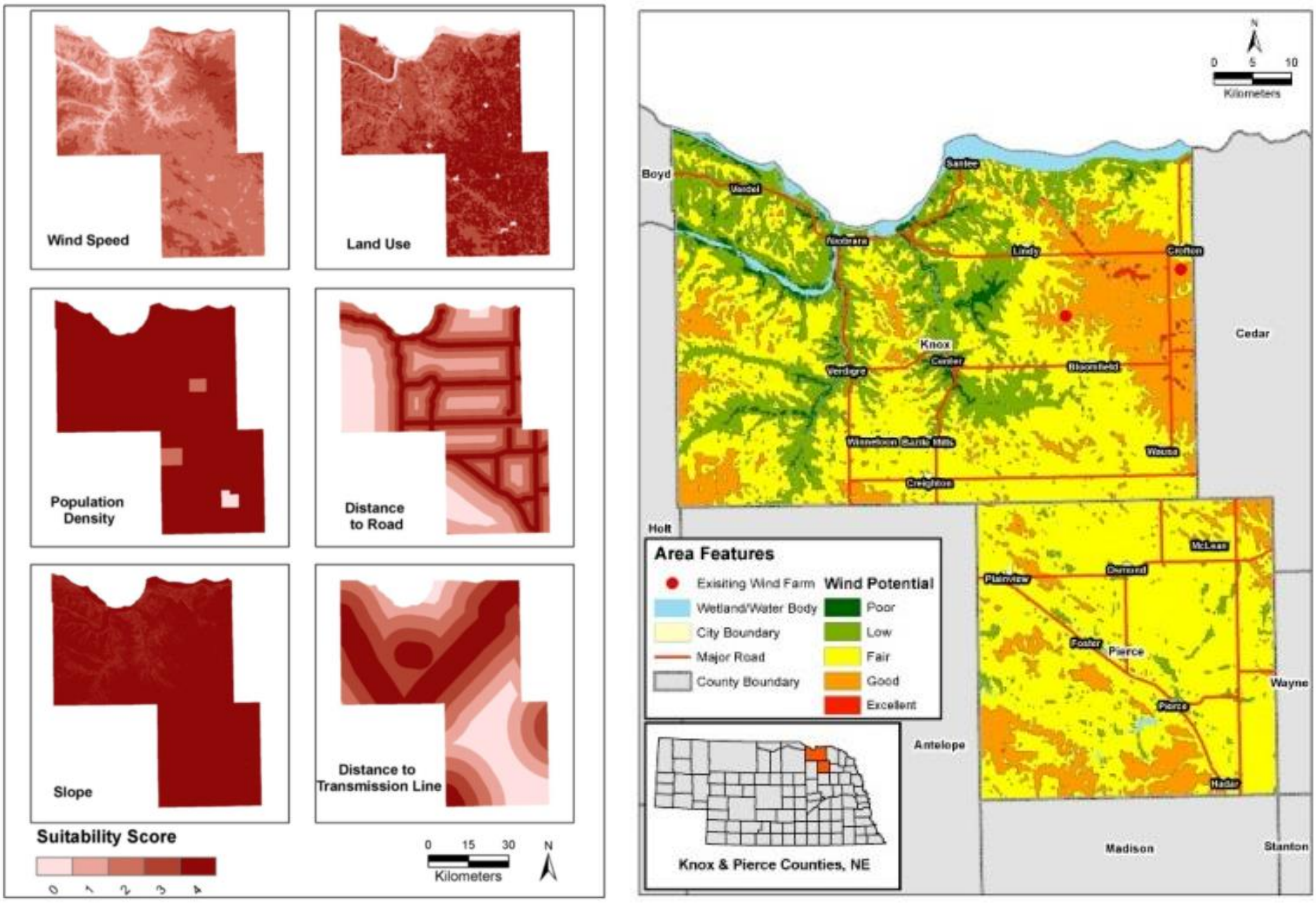


Figure 25 Process of modelling a wind farm using certain criteria in ArcGIS Pro [111]

## 1.3. LITERATURE GAP AND RESEARCH QUESTIONS

An important take-away from the literature is that selecting of suitable areas for these low costs large-scale projects is done by looking at the resource availability only, while there are also other factors that determine the suitability of a site for green hydrogen production. In addition, cheap green hydrogen is possible but to produce it on a gigawatt-scale in the future the amount of space with good to excellent renewable resources in a region is essential. But the main issue, which will determine the overall potential for green hydrogen production in Europe, is knowing exactly how much available space there is for these systems and how much space is really needed for these large-scale projects.

To effectively determine whether a location is suitable for large-scale green hydrogen production one must include restriction areas such as cities, airports, and areas of natural beauty. Also consider social, geographical, and technical factors. In addition, large-scale green hydrogen projects are estimated to be around 500km$^2$ of solar PV and 1000km$^2$ for wind as renewable electricity source as this is the area estimated to be needed for the production of 1 million tons per year. 1 million tons per year will fill the medium-sized pipelines of the hydrogen network in the future, further explained in chapter 2.2. With ArcGIS Pro a suitability model can be made with the aforementioned factors to indicate how much area there is available for the production of large-scale green hydrogen.

This research will examine the technical- and economical hydrogen potential of countries in Europe and in North-Africa using a geospatial analysis. This considers solar and wind resources, and constraints from population density, environmental areas, airports, and cities for solar PV, wind, and a combination of solar PV and wind as an electricity generator for electrolysis. This model will show how much space there really is to implement this scale of green hydrogen production. In short, this research will try and find the answer to the main research question and sub-questions. The main research question is stated below.

*“ What is the potential for low-cost large-scale green hydrogen production in Europe and the Mediterranean region in 2030 & 2040?”*

The term low-cost is used in this research to indicate levelized costs of hydrogen below 1.5€/kg. This is the price of grey hydrogen production with a $CO_2$ price of 50 €/kg, 1.0 €/kg for the production of hydrogen and 0.5 €/kg for the $CO_2$ price [10].

The term large-scale means that a production of around 1 million tons of hydrogen is needed to fill the medium sized pipelines in Europe.

To accurately answer the main research question, the following sub-questions are proposed.

1. What is the levelized cost of hydrogen in 2030 & 2040 throughout Europe and the Mediterranean region as a function of the solar and wind resource?

2. Where are suitable locations and how much space is available in Europe and the Mediterranean region for large-scale green hydrogen production?

3. What is the hydrogen production potential for large-scale low-cost (<1.5 €/kg) in Europe and the Mediterranean region in 2030 & 2040?

4. How can ArcGIS pro be adapted, handle input data and be validated for these hydrogen cost and potential calculations?

The research will start by explaining the methodology in chapter 2. A workflow is presented to indicate how the research is conducted. This chapter will show how the how the suitable areas are selected in ArcGIS Pro-, show how the yield for the solar and/or wind system-, levelized cost of hydrogen-, and how the hydrogen production potential is calculated. Chapter 3 describes the results, and chapter 4 discusses these results. Chapter 5 gives the conclusions of this research by answering the main research question and sub-questions and will give recommendations for future work.

# 2 METHODOLOGY

This chapter describes the methodology of the geospatial techno-economic analysis. In 2.1 the research approach is depicted with a workflow. Then, in 2.2 the system boundaries and design are described. In 2.3 – 2.5 the methodology behind the geographical-, technical-, and economical hydrogen potential is shown. In 2.6 the methodology for calculating the area- and electrolyzer size needed for a production minimum of 1 million tons for the solar and/or wind scenario is shown. In 2.7 the input values for the models are depicted.

## 2.1 METHOD

For this research, a geospatial assessment of the techno-economic green hydrogen potential in Europe and North-Africa is done. The most important steps for this study are shown in figure 26 and are explained in the following sub-sections.

Firstly, the geospatial part indicates the solar and wind resource potential in Europe and North-Africa using spatial restricted zones. This part is done by using a GIS application called ‘Model builder’. GIS has been used for the assessment of energy resources since 1990 and has made good progress since then; examples for the use of GIS for this type of research are shown in [75][76][77]. GIS can be used to locate energy resources of a regional or global such as wind, solar, hydropower etc. Now the suitable regions are limited to resource availability, siting criteria and restricted areas.

Secondly, a techno-economic analysis evaluates the technical and economic performance of a product, system, service, or in this case the technical potential and economic indicators of these suitable regions in 2030 and 2040 [78]. The regions are then limited to the technical potential after considering the technical parameters of wind and solar equipment. The cost assessment includes the capital expenditure, operational expenditure, lifetime, weighted average cost of capital of these devices. For this research, the annuity method is chosen, which spreads the investment costs of the lifetime of a project. This is a wide range used method in Europe, and especially for preliminary projects. In addition, this method is also used in previous techno-economic studies of hydrogen supply chain [79]. In addition, with the technical parameters of the electrolyzer and renewable energy system size per available area the total green hydrogen production potential is determined. With this potential the Levelized Cost of Hydrogen per region is determined for 2030 and 2040, using the concept of Levelized Cost [80]. Using a top-down approach the steps for retrieving the LCOH are explained [82]. Knowing the LCOH provides the information needed to determine the effect of introducing green hydrogen into the European energy system.

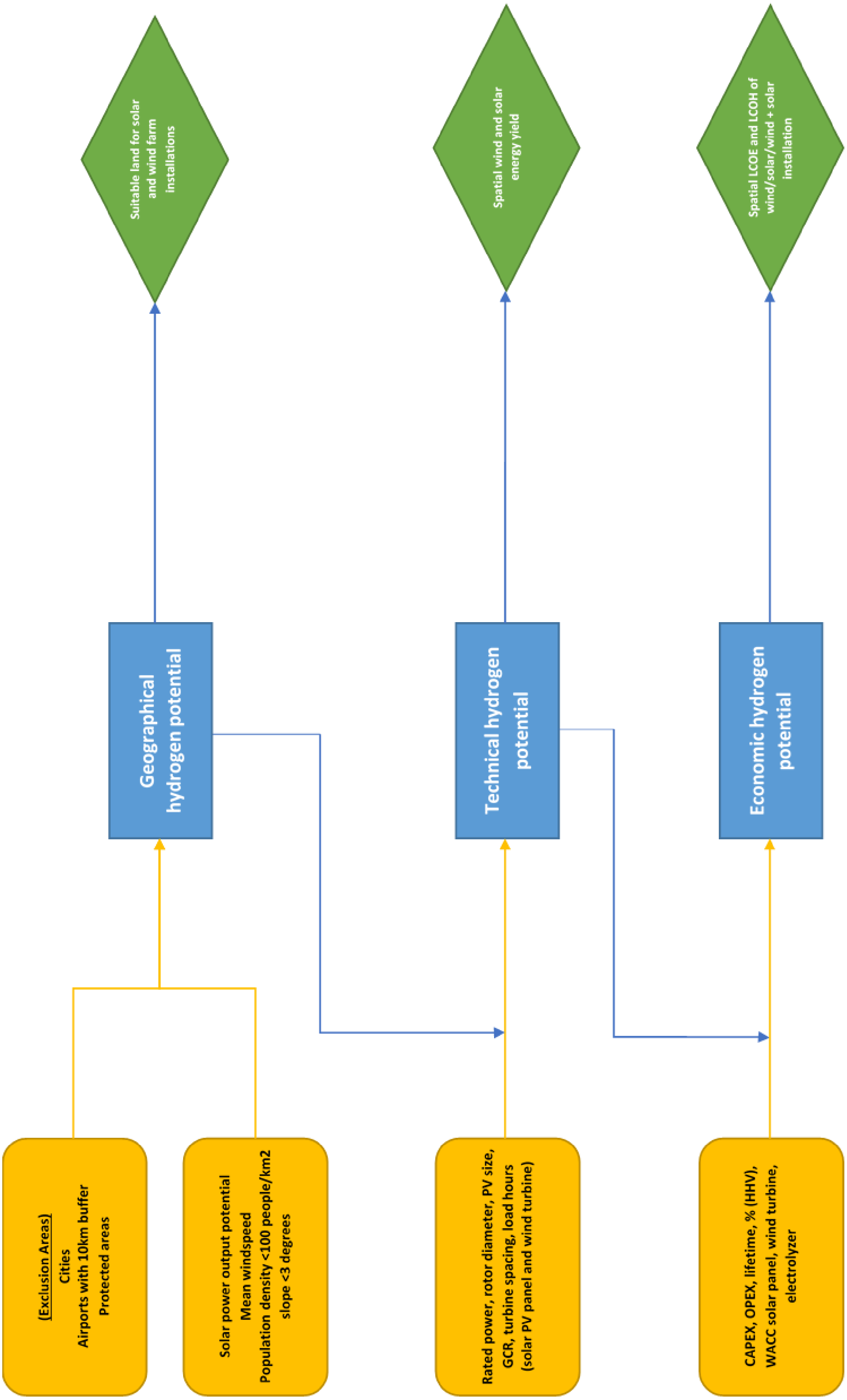


Figure 26 Workflow research. First the geographical hydrogen potential is determined and then the technical hydrogen potential. Last the economic hydrogen potential is calculated and this gives the Levelized costs of hydrogen

## 2.2 SYSTEM BOUNDARIES AND DESIGN

The geospatial assessment of the techno-economic analysis includes a number of parameters that are relevant for this research, but it is important to firstly set the scope of this analysis. The countries considered for this research are shown in Appendix A. Russia is not considered as a larger part of Russia is not feasible for the use of this research and the distance to the Europe is too large from certain areas in Russia. In addition, the oceans are not considered for this research due to lack of solar and wind data.

The next element is to determine the size of a large-scale green hydrogen production system. The pipeline system in Europe varies between a ‘small’ 20-inch diameter one to 48-inch diameter ‘large’ sized pipelines. For this research, a medium-sized 36-inch gas pipeline is considered, as this is the average size of a pipeline for the European gas network system [81][82]. A medium-sized pipeline can transport around 10 GW of natural gas (HHV), which is around 1 million tons of hydrogen [10]. Looking at other initiatives for large-scale green hydrogen production, table 3 shows that the average amount of production is between 0.5 – 3.6 million tons of hydrogen for these large-scale projects. A 10 GW electrolyzer system is estimated to produce around 1 million tons of green hydrogen per year in the most optimal regions e.g., NortH2 & AquaVentus. Therefore, the average production size of a large-scale green hydrogen system is estimated around 1 million tons per year for this research.

Next, the available area needed for the system to produce 1 million tons of green hydrogen per year differs per renewable energy source. For solar, to research how much area is needed to produce 1 million tons of hydrogen the yield needs to be determined. The yield differs per latitude and to consider this element the Ground Coverage Ratio (GCR) needs to be determined. The GCR is the amount of area covered by solar panel placement divided by the whole area taken for the solar panel project. Solar panels placed in the Sahara have a higher GCR than in Sweden due to the angle of the sun [45]. The solar panels are all assumed to be facing south-wards for optimal solar power output. As the ground coverage ratio differs from 0.34 – 0.45 for these regions the area is estimated to be around 80 km2 for the most optimal regions and 180 km$^2$ for the least optimal regions in 2040 and 90 – 210 km$^2$ for 2030. But, because certain aspects such as slope aspect and efficiency losses due to e.g., temperature, the total area size is much larger. To compensate for the exclusion of these elements the area size is estimated to be 500km$^2$ for solar energy. The area size needed for this scenario is assumed the same for 2030 and 2040.

For wind, to research how much area is needed to produce 1 million tons of hydrogen using only wind turbines the spacing between wind turbines is considered. The turbines are assumed to be 6 MW for 2030 [47] and 10 MW for 2040 [46]. The normal spacing between wind turbines is set between 6-10 times the rotor diameter. The most optimal spacing ensures for maximizing the space used for wind turbine placement. In a more in-depth research, the spacing factor is determined by looking at wind speeds ratios and directions, type of turbine, land costs and size. For this research, this is not looked at as these factors vary between state, cities, and small towns, so a general wind turbine spacing is taken of 6 times the rotor diameter for all the areas suitable for wind turbine placement [50]. As mentioned, the rotor diameters for the wind turbines differ for the wind scenario in 2030 and 2040, thus giving a different turbine spacing [46][47]. Although the spacing between turbines is larger in 2040, the Power/km$^2$ is larger of the 10MW turbine, thus compensating for the lost space between wind turbines. The power/km$^2$ for the 10 MW is 7.45 MW/km$^2$. Knowing the power/km$^2$ for the wind turbines the estimated area needed is 1000km$^2$ for the most optimal areas and 2000km$^2$ for the least optimal areas in 2040. Although the average area size is around 1500 km$^2$ the threshold is 1000 km$^2$ for this research.

For the solar and wind scenario it is assumed that the solar panels and wind turbines are placed directly next to each other to make optimal use of available space. Therefore, the same area size is considered as for solar energy.

It is assumed that the system size of the renewable energy system is equal to the electrolyzer capacity used and that the solar and wind resources are variable, which calls for oversizing of the wind and solar hybrid system. It is assumed that hydrogen is only produced when electricity is produced, and the variability is covered by hydrogen storage. Hydrogen is assumed to be operated at baseload but depends on the final costs when it is transformed to baseload.

## 2.3 GEOGRAPHICAL HYDROGEN POTENTIAL VISUALIZATION WITH GIS

This sub-chapter shows the scenarios selected for the suitability analysis. The Russian Federation has not been considered for the final suitability maps of all three scenarios but has been included in first datasets as comparison for other countries.

### 2.3.1. SELECTION OF MODELING FACTORS FOR GIS

All the layers considered in ArcGIS Pro and were extrapolated onto GCS_WGS_194, a one-size-fits-all geodetic system to change the data from vector to raster. For this model, and the other two, a common cell size is used. The criteria and their reason for selection, data source, original data structure and feature type are depicted in table 4.

The datasets for the feasible areas include data on solar PV power output potential over Europe and Mediterranean region. It was retrieved from Global Solar Atlas [BRON] that provides spatial data at a global level in raster format with a resolution of 1 km. In addition, global slope data is collected from ESRI, which is sourced from different meteorological institutes and companies. Population density is also provided by ESRI and is predefined in 5 classes ranging from Rural, less than 100 people per km$^2$, to Extreme Urban, more than 50.000 people per km$^2$ [17]. Mean windspeeds at 150m height over Europe and Mediterranean region was retrieved from Global Wind Atlas [25] that provides spatial data at a global level in raster format with a resolution of 1 km.

An important aspect for solar PV and wind turbine placement is the degree of slope. A slope that is too high means extra trouble with placement [21]. The pixel size is adjusted to that of the Global Solar Atlas dataset to make configuration of both dataset easier.

The geoprocessing tools used for this model are depicted at the start of this chapter in table 4.

**Table 4 Geoprocessing tools used for modelling the geospatial analysis**

| | |
|---|---|
| Buffer | Creates a buffer polygon with a particular distance around features in the raster. Restricted areas e.g., airports and cities are defined by this tool |
| Reclassify | This tool reclassifies the raster into certain intervals and gives the values valid statistics. This is used to set intervals in all datasets to make modelling simpler and define different Renewable Energy generating areas |
| Resample | The tool alters the spatial resolution of a raster and sets boundary values with new pixel size |

| | |
|---|---|
| Extract by Mask | Extracts certain set raster cells defined by a mask. This is used for selecting the countries in this research |
| Weighted Sum | Multiplies raster input values by a specified weight. All rasters are then summed up together with the weights to create an output raster |
| Raster Calculator | This tool makes it possible to create and execute an algebra expression that create an output by defined boundaries. This is used to separate different areas after the weighted sum is applied in these models |
| Weighted overlay | This is used to overlay and multiply different rasters to create an output. The restricted areas are multiplied by the suitable areas to evaluate the model further. |
| Raster to polygon | This converts a raster file to a polygon feature. This tool is used to calculate the geometry of the suitability analysis per model. |
| Select | Extracts features from one class using a selection expression. This is used to filter suitable areas above a certain $km^2$ |
| Clip | Slices out one or multiple features from other features. To obtain the amount of $km^2$ per country per model a Clip tool is used |
| IsNull | Returns 1 if the input is 0 or has Nodata in the cells. This is used to characterize the restricted areas in all the models. |
| Merge | Combines multiple datasets into a single dataset, used for the restriction areas |

### 2.3.2. RESTRICTED AREAS

First the restricted areas are determined as this dataset is applied to each model to acquire the final sutiability map.

The restricted areas have been buffered for exclusionary areas with environmentally sensitive areas (e.g., Area of natural beauty) and human sensitive areas (e.g., cities, and airports). The buffer distance stems from literature research and is depicted in table 5.

**Table 5 Restricted areas criteria and buffer distance. A buffer of 10000m is used for airports in the model**

| Restricted areas | Buffer (m) |
|---|---|
| Protected areas | 0 |
| Airports | 10.000 (based on safety procedures and turbulence coming from wind turbines and assumption. |
| Cities | 0 |

Protected areas and cities are set to 0m buffer distance because the proximity for wind turbine and solar panel placement is small for areas of natural beauty and therefore not considered for this research [23].

Most studies show similar buffering distance for airports. For this research, a buffer distance of 10.000m is taken for safety reasons and to account for high mean windspeed areas that create strong turbulence near airports [24][95].

In the figures 27-29 the components, cities/airports/protected areas, are depicted and in figure 30 the final map for restricted areas is shown for Europe and North-Africa.

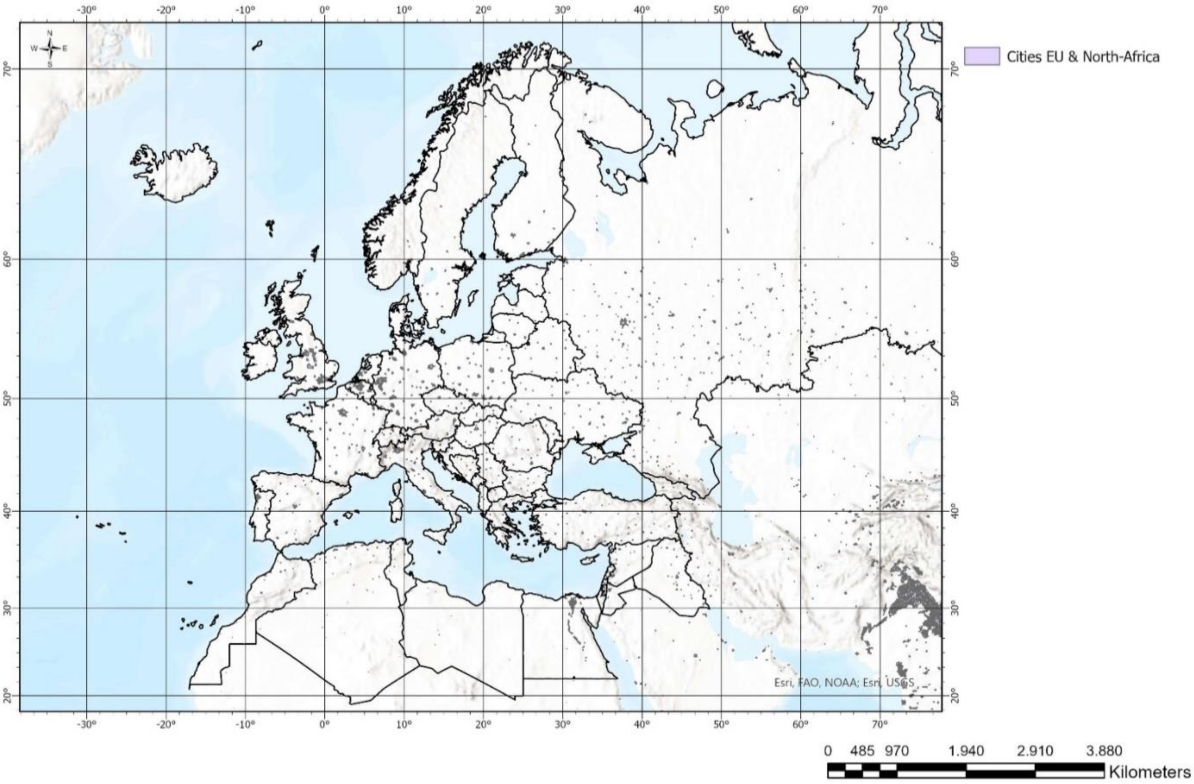


Figure 27 Cities in Europe & North-Africa

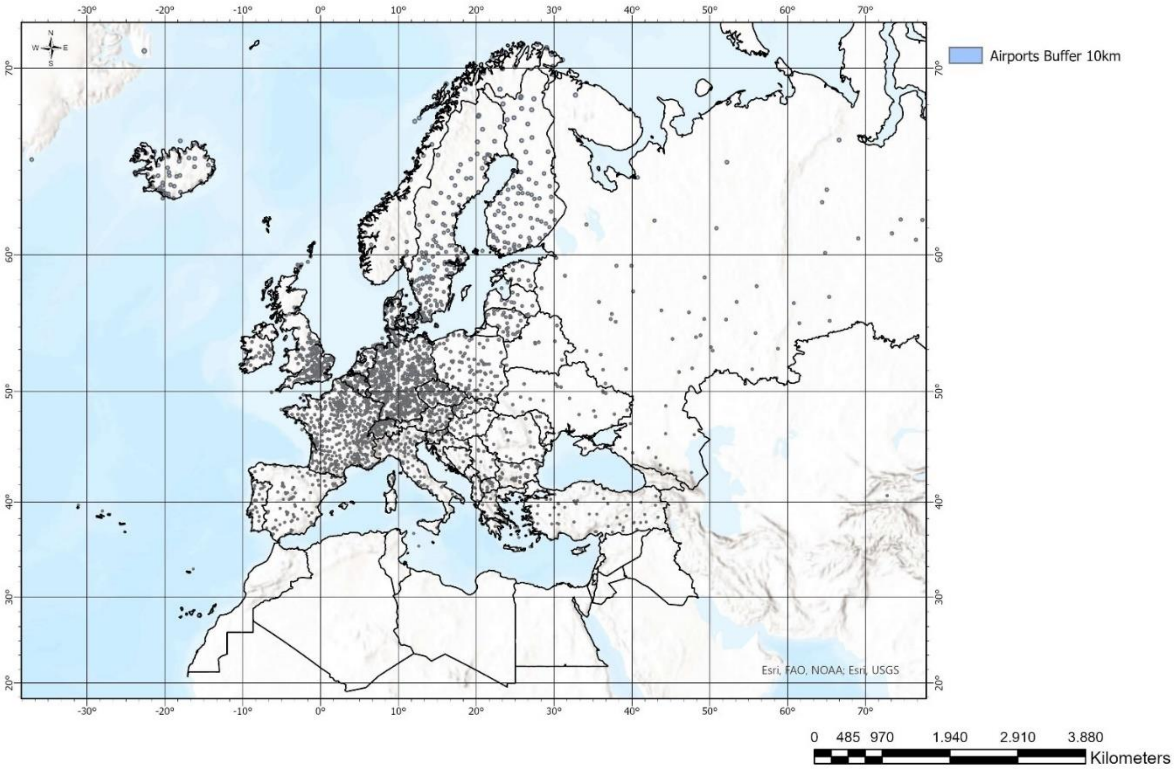


Figure 28 Airports in Europe and North-Africa with 10km buffer

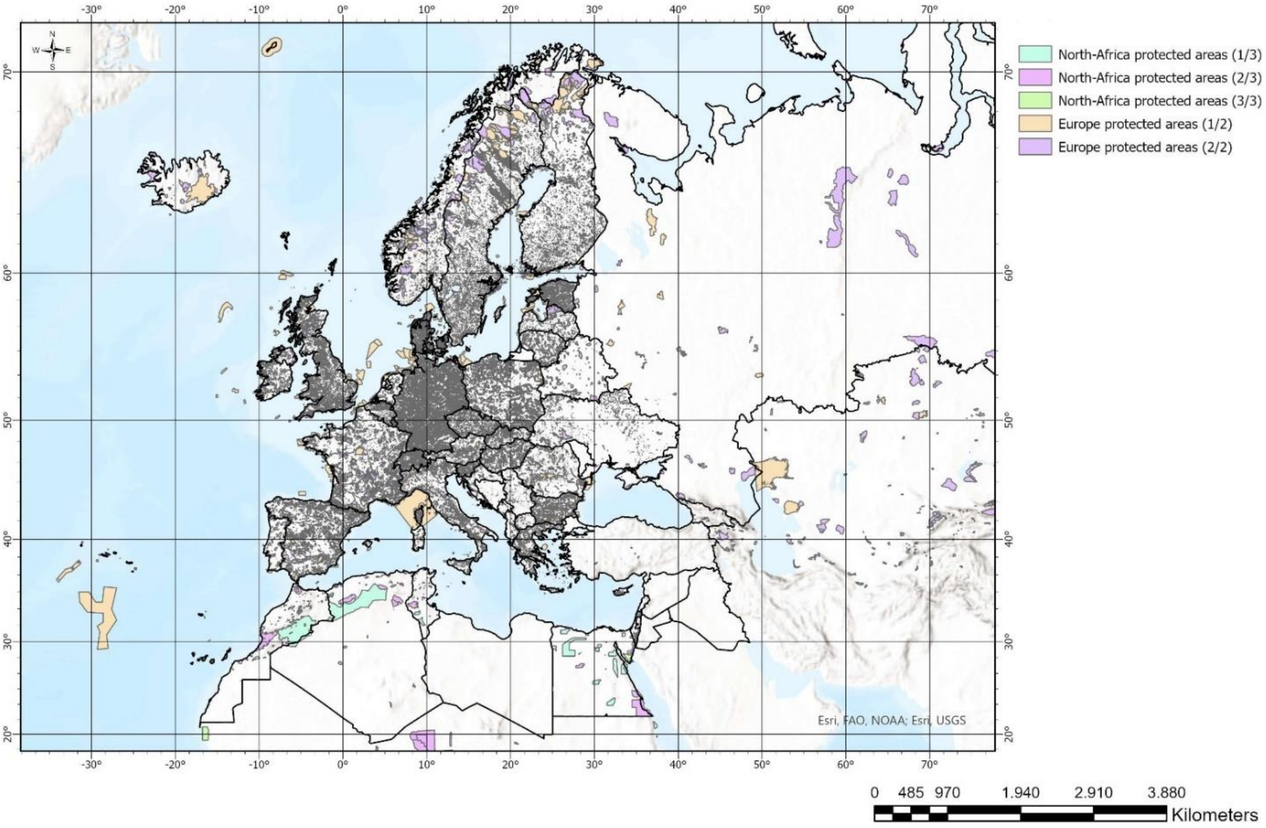


Figure 30 Protected areas in Europe and North-Africa

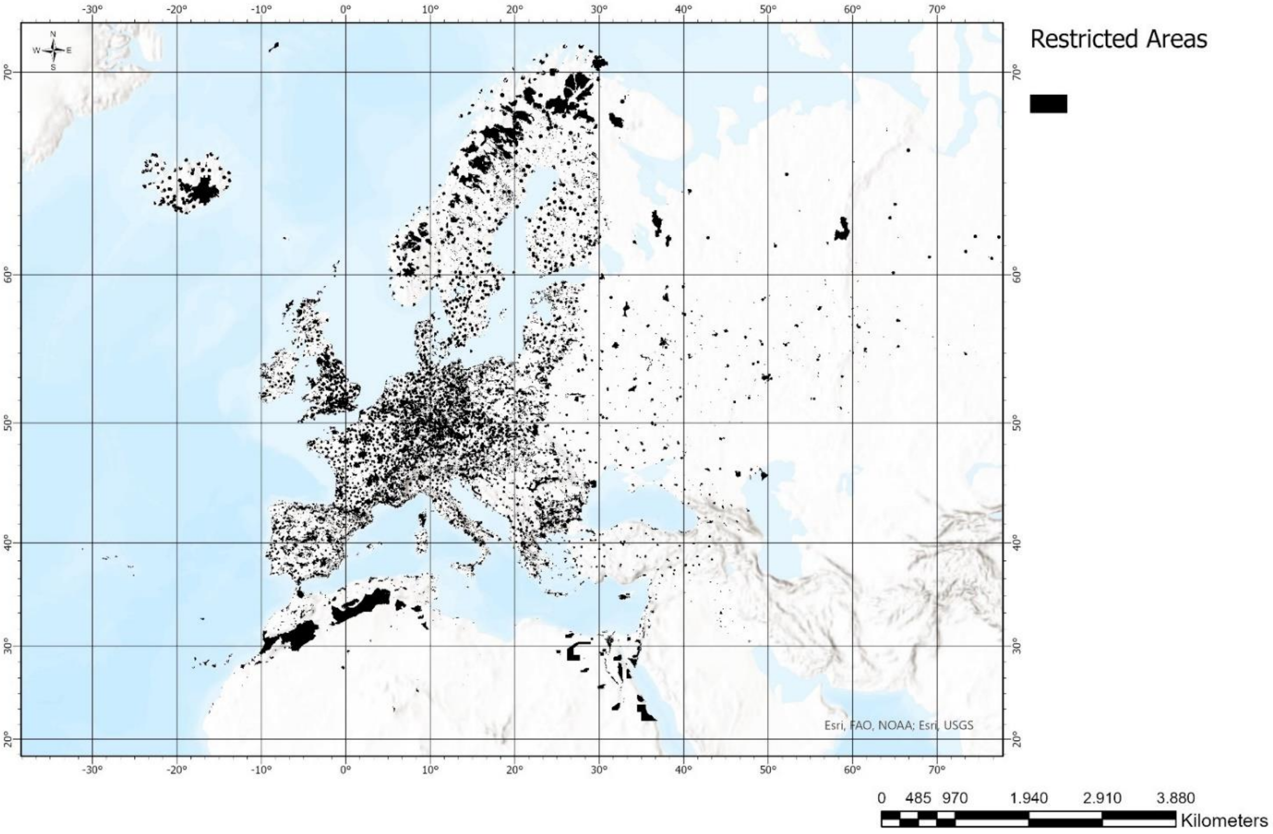


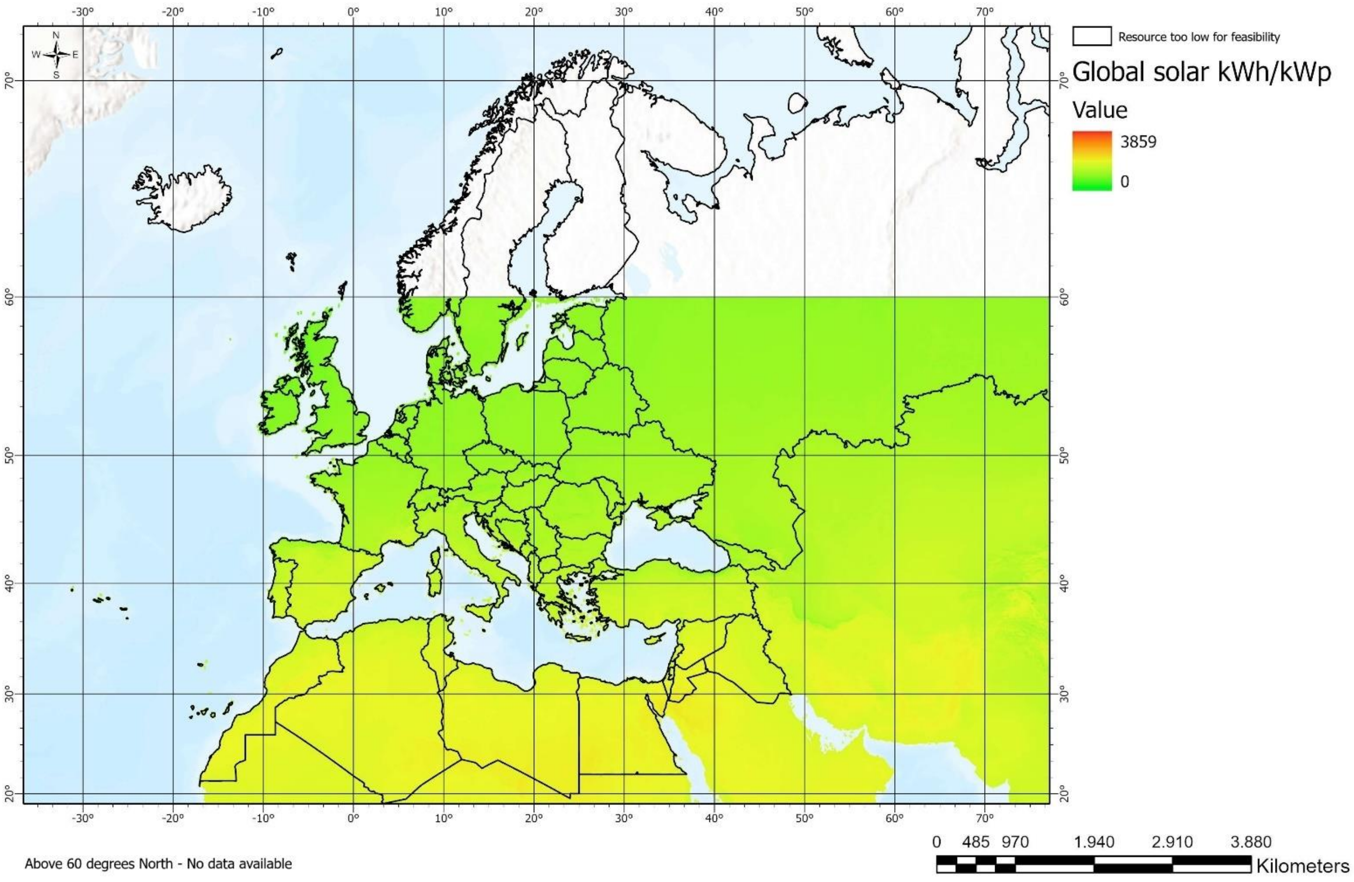
Figure 29 Restricted areas (Cities, Airports and Protected areas) in Europe and North-Africa

## 2.3.3. SOLAR PV SYSTEM SITE SUITABILITY

This scenario shows the modelling of only the solar panel potential power output as an electricity generator for green hydrogen production. In addition to the solar scenario, different criteria are also used in this model to accumulate for the geographic specifications of solar panel placement e.g., slope. Also, solar irradiation data is confined to 60 degrees North latitude due to lack of data from this latitude and higher up North.

### MODELING PROCESS

The power output potential and population denisty are first resampled with a common cell size of (X,Y)(0.013,0.013) in the ArcGIS Pro modelbuilder, using a nearing sampling technique. This performs a nearest neighbour interpolation by assuming the intensity of the cell value and doesn’t change the value of the cell.



Data obtained from the "Global Solar Atlas 2.0, a free, web-based application is developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalsolaratlas.info; Esri, FAO, NOAA; Esri, USGS

**Figure 31 Global solar output potential kWh/kWp in Europe and North-Africa. The highest output in North-Africa. [15]**

In figure 31 the global solar output potential is shown in kWh/kWp. The global power output potential dataset is then reclassified into a suitability rating of 1-7, depicted in table 6.

The intervals are set to 200 kWh/kWp difference between classes as to keep the amount of classes even between the wind- and solar energy scenarios.

**Table 6 Classification solar power output potential [kWh/kWp]. An interval of 200 kWh/kWp is sufficient for the scale of this model**

| Rating | Power output potential (kWh/kWp) |
|---|---|
| 1 | 800-1000 |
| 2 | 1000-1200 |
| 3 | 1200-1400 |
| 4 | 1400-1600 |
| 5 | 1600-1800 |
| 6 | 1800-2000 |
| 7 | 2000-2200 |
| NODATA | 0-799.99 |
| *NODATA in selected areas* | *2200-2470* |

The boundaries set for this dataset are larger than 800 kWh/kWp, as below this value it is not feasible to place solar panels e.g., in areas such as North-Norway. Also the upperboundary is 2200 kWh/kWp, as above this value there are no existing areas located in this research. Then only Europe and North-Africa are extracted from the layers, shown in Appendix A. This is shown in figure 32.

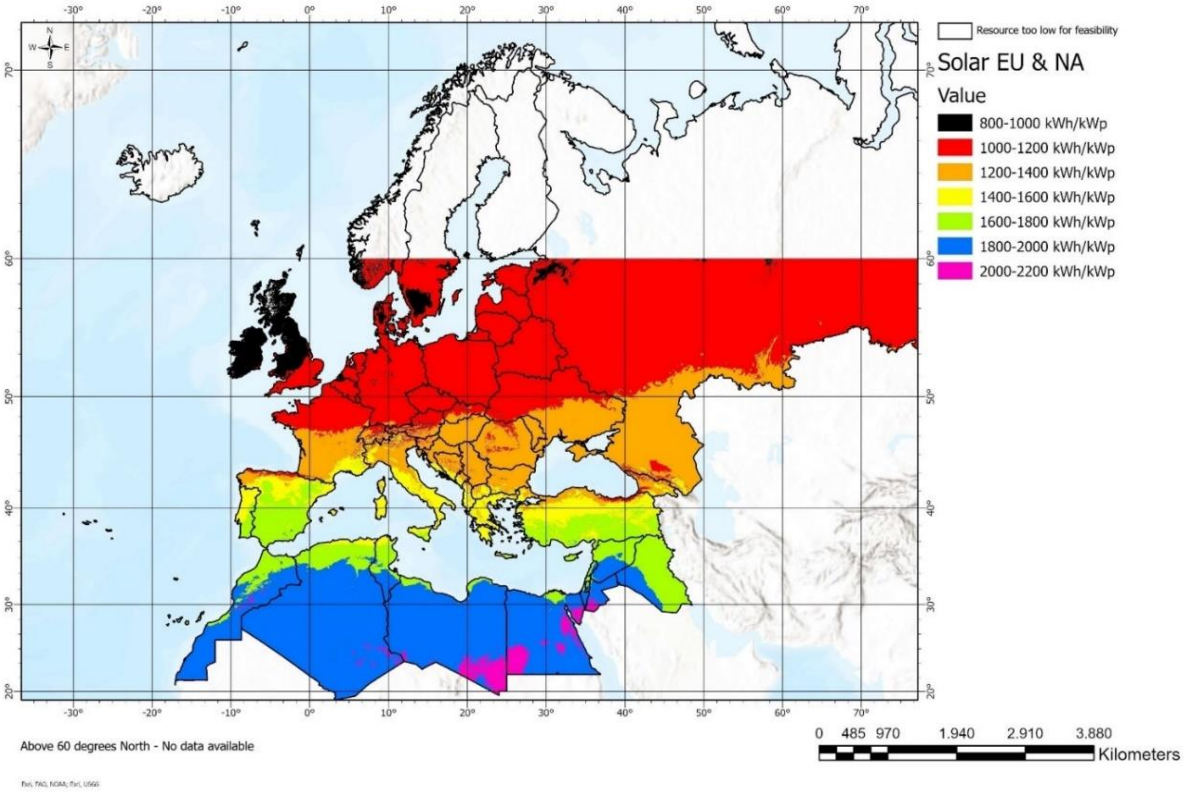


Figure 32 Extracted Reclassified Solar power output potential in Europe and North-Africa

The population density is already a classified raster dataset and is rated from 1-6, indicating the amount of people per km$^2$, depicted in table 7 and depicted in figure 33.

Table 7 Classification of population density dataset

| **Rating** | **Interval (People/km$^2$)** |
|---|---|
| Rural | <100 |
| Settled | <400 |
| Light Urban | >1.908 |
| Urban | >16.978 |
| Heavy Urban | >26.331 |
| Extreme Urban | >50.000 |

Because only the Rural and NODATA areas are of interest for this research, the other classes are set to NODATA and Rural and the predefinied NODATA areas is set to 1. Shown in figure 33 and 34.

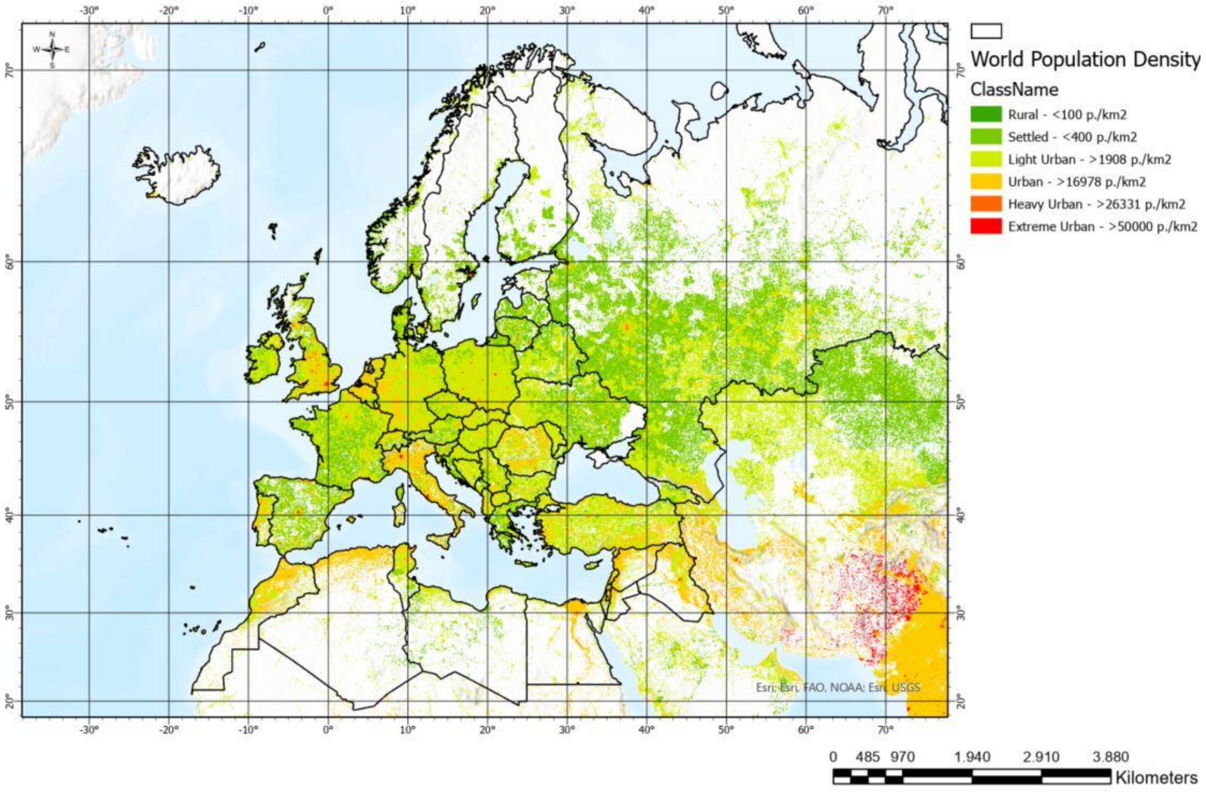


Figure 33 Classification Population density in Europe and North-Africa. Areas in urbanized regions have the highest population density.

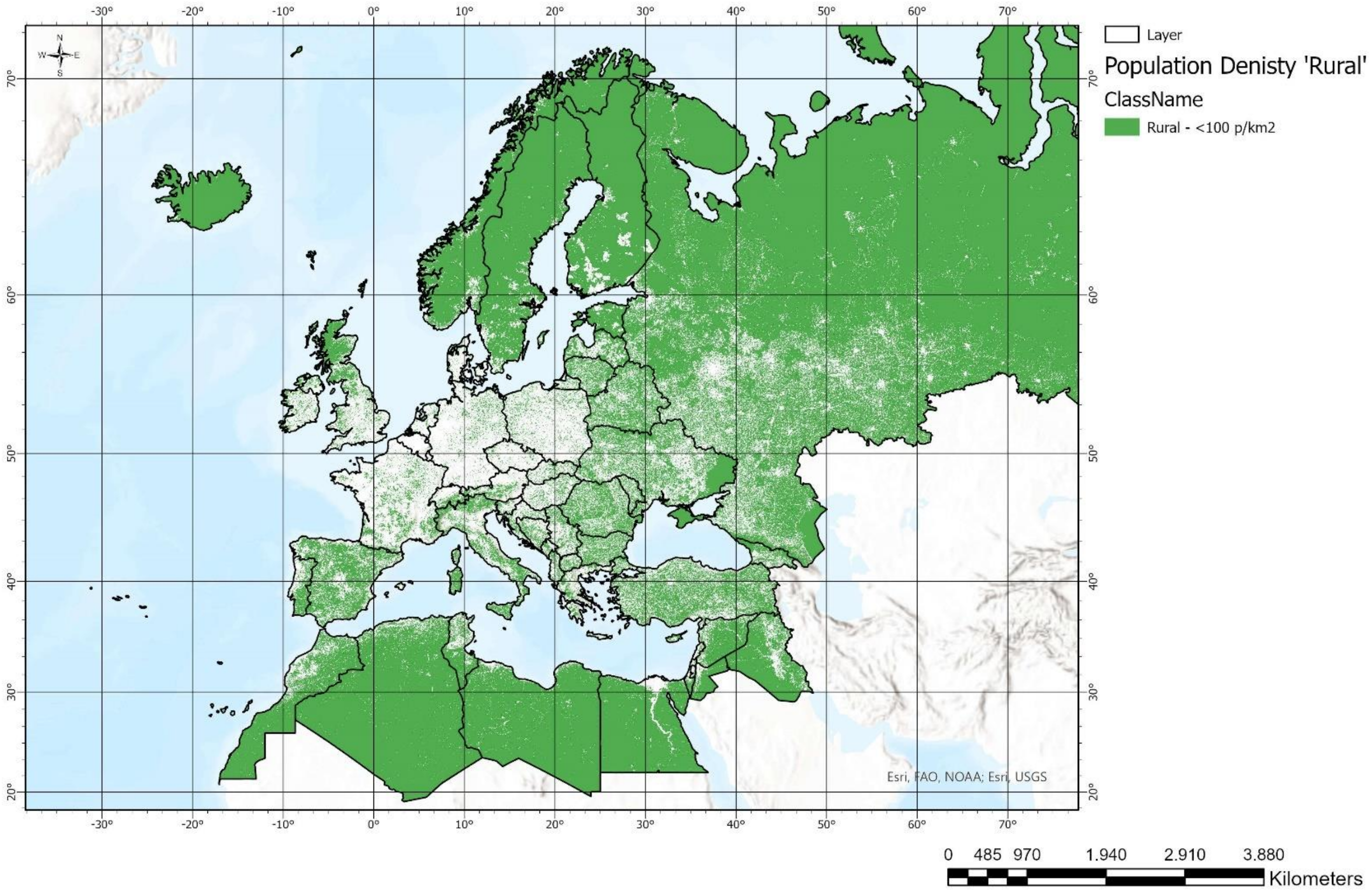


**Figure 34 Population density 'Rural'. All urbanized areas are filtered from the original map.**

The same is done for the slope dataset. For this dataset, the maximum slope is taken at 3 degrees. According to [22] the maximum slope used for a solar panel placement is set at 10 degrees. Because the data calculates an average for the slope, due to pixel size, the slope is set at 3 degrees and not higher to filter out the mountainous areas, see table 8.

**Table 8 Reclassification of the slope in degrees. Every slope angle above 3 degrees is considered too high for solar PV and wind turbine placement**

| **Rating** | **Interval (degrees)** |
|---|---|
| 1 | 0 – 1 |
| 1 | 1 – 2 |
| 1 | 2 – 3 |
| NODATA | 3 – 5 |
| NODATA | 5 – 9 |
| NODATA | 9 – 13 |
| NODATA | 13 – 90 |

Figures 35 and 36 show the slope in degrees and reclassified slope in degrees to 1-3 degrees.

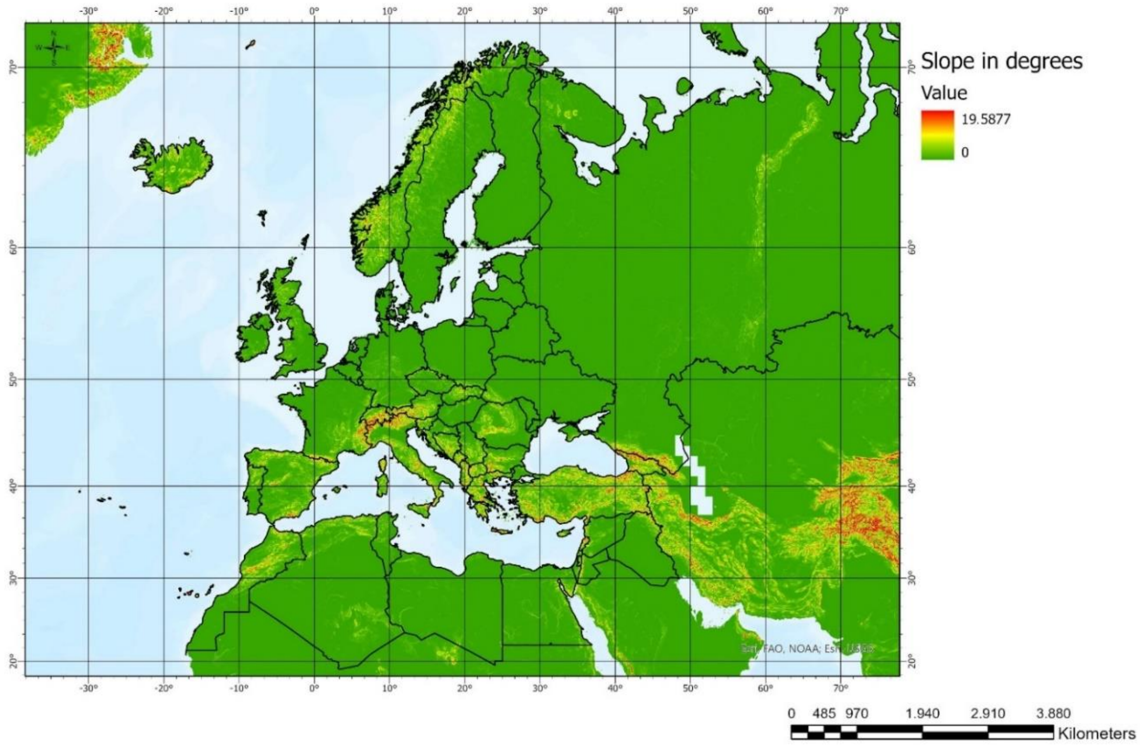


Figure 35 Slope in degrees in Europe and North-Africa. The highest slopes are located in mountainous areas.

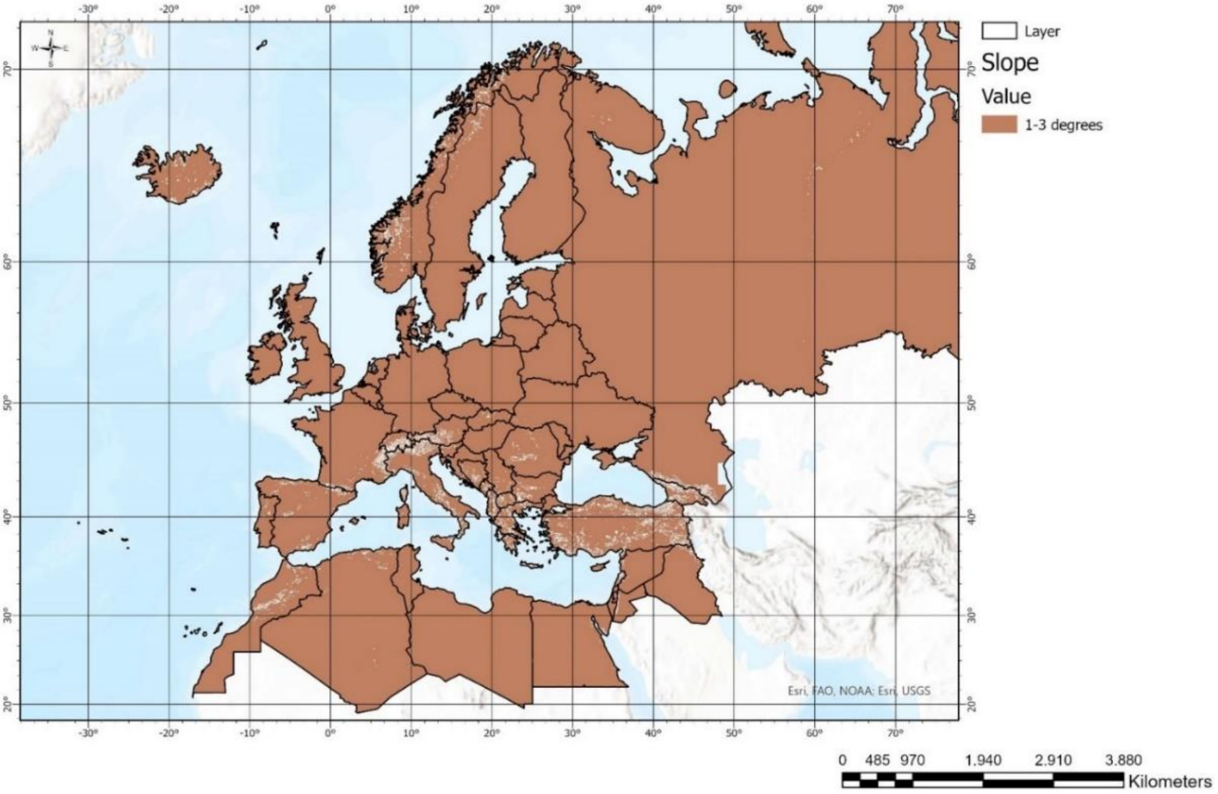


Figure 36 Slope reclassified 1-3 degrees. All mountainous areas are filtered from the map.

The datasets are then assigned a certain weight in a Weighted Sum tool to locate suitable areas. The weights are appointed to every layer to indicate a certain significance of the layer to the model. The power potential output is imperative to the model of locating suitable areas for a solar power generated green hydrogen electrolysis plant. Slope and population density have the same weight as the power potential to only depict the areas with a certain slope and population density. This is shown in table 9 and depicted in figure 37.

Table 9 Weighted sum solar criteria and weight. Each dataset has the same weight for simplicity.

| **Criteria** | **Weight** |
|---|---|
| Solar power output potential | 1 |
| Slope | 1 |
| Population density | 1 |

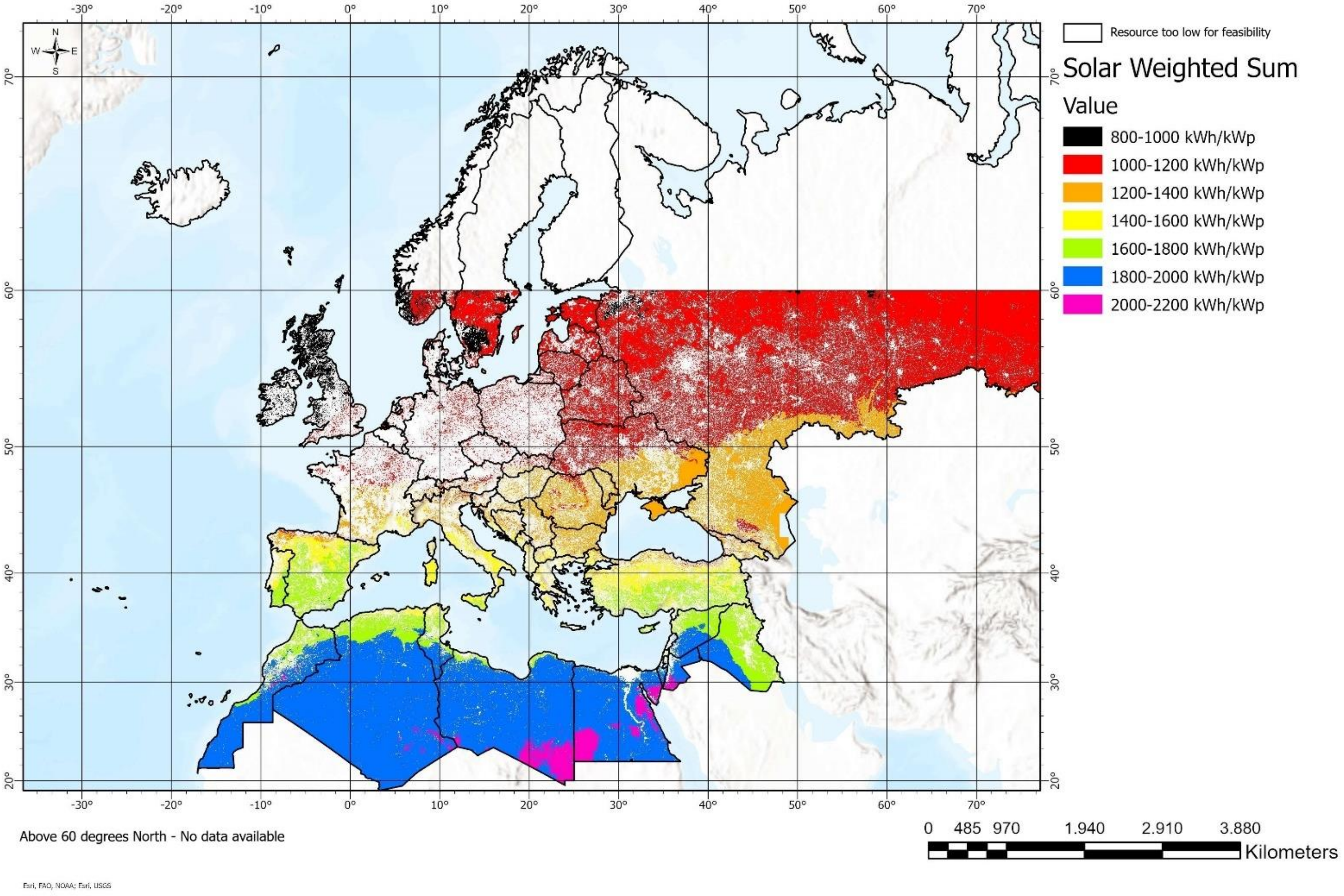


Figure 37 Solar power output potential weighted sum. The amount of available area is reduced due to the slope and population density datasets.

The merged reclassified layers are then merged into a suitability map, excluding the restricted areas, with the final suitability scores per area ranging from 1 (low-solar power potential output) to 7 (high-solar power potential output). To depict the layers separately a raster calculator tool is used so that we can calculate the potential of hydrogen production per area. These 7 areas are set to the final weighted sum score to extract the areas per solar power output potential class. This is shown in table 10.

**Table 10 Solar area number with power output interval. The region with the lowest power output is Area 1 and the highest is Area 7.**

| Rating | Solar Area number | Power output (kWp/kWh) |
|---|---|---|
| 1 | Area 1 | 800-1000 |
| 2 | Area 2 | 1000-1200 |
| 3 | Area 3 | 1200-1400 |
| 4 | Area 4 | 1400-1600 |
| 5 | Area 5 | 1600-1800 |
| 6 | Area 6 | 1800-2000 |
| 7 | Area 7 | 2000-2200 |

The restricted areas are excluded from the reclassified geospatial raster datasets and the final suitability area, in raster format, is then shown in figure 38. The final suitability raster is then put into polygon format for geometry calculations of all the areas in the datasets.

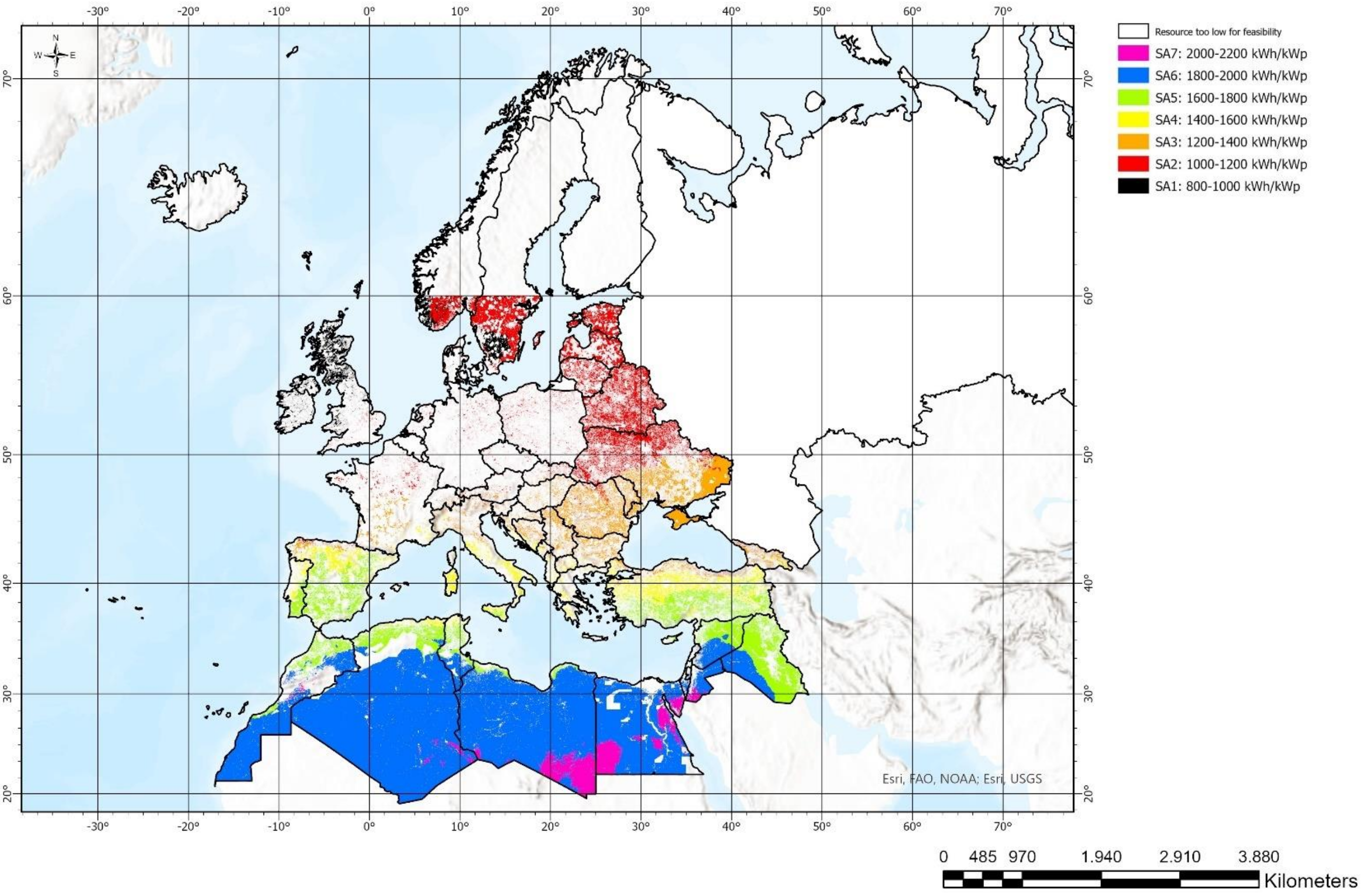


Figure 38 Suitability map solar scenario. The most suitable areas are located in North-Africa.

With the polygons it is possible to use the ‘Select’ tool and filter the areas smaller than 500km$^2$ from the suitability maps. The final suitability map with size criterion is depicted in the Results chapter.

To calculate the geometries of the areas per country a Clip tool is used to extract this from the final suitability map and is then used in the cost calculations model, shown in the financial modelling chapter.

## 2.3.4. WIND TURBINE SYSTEM SITE SUITABILITY

This scenario shows the modelling of only wind power as an electricity generator for green hydrogen production. In addition to the solar scenario, different criteria are also used in this model to accumulate for the geographic specifications of wind turbine placement e.g., slope.

### MODELING PROCESS

The mean windspeeds and population denisty are first resampled with a common cell size of (X,Y)(0.013,0.013) in the ArcGIS Pro modelbuilder, using a nearing sampling technique. This performs a nearest neighbour interpolation by assuming the internsity of the cell value and doesn’t change the value of the cell.

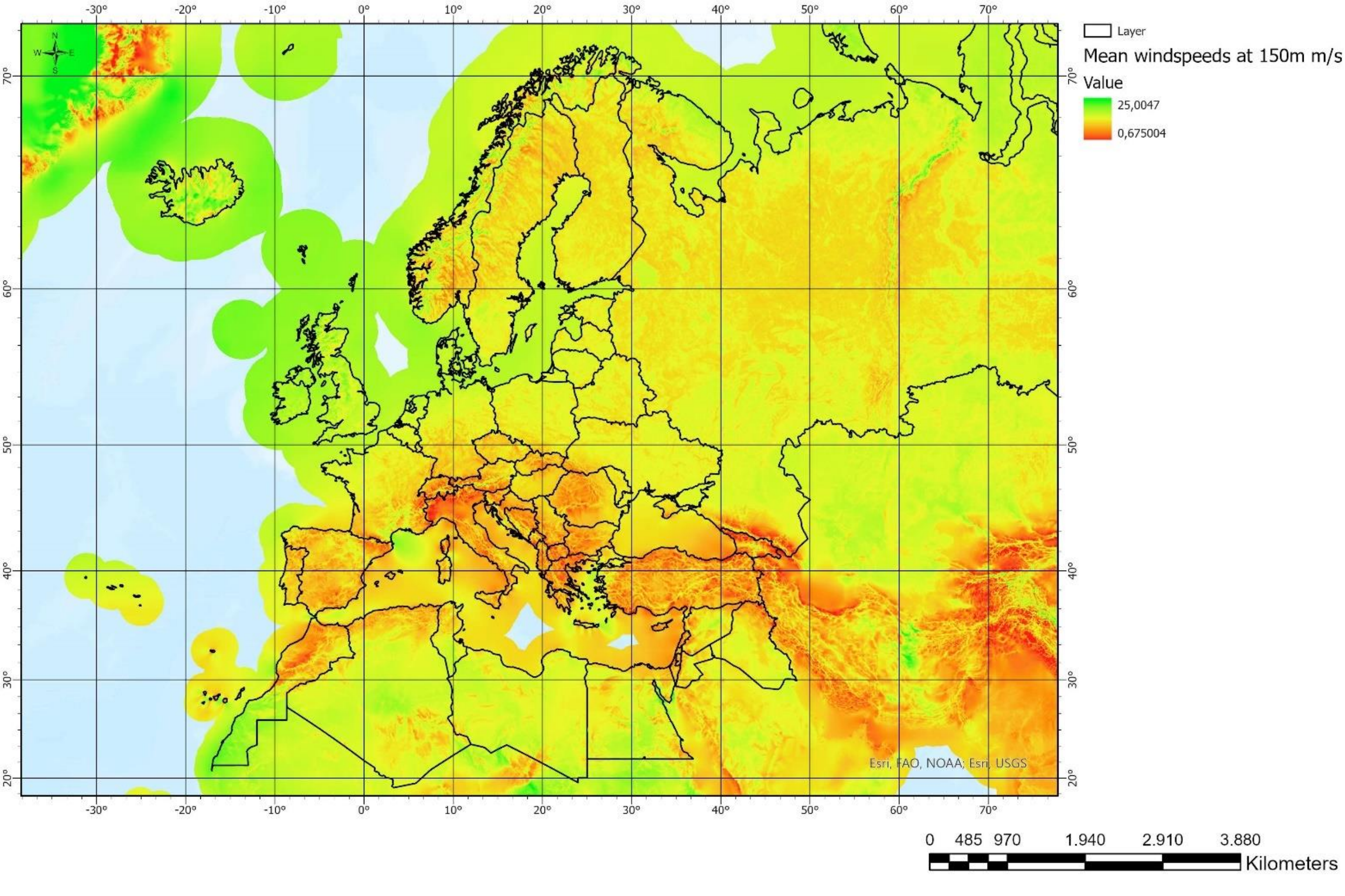


Figure 39 Global Mean windspeeds at 150m m/s. The highest wind speeds are located in North-Europe and North-Africa.

In figure 39 the global mean windspeed is shown in m/s.The mean windspeeds dataset is then reclassified into a suitability rating of 1-7, depicted in table 11.

The intervals are set to 1 m/s difference between classes as this is the sensitivty of the windturbine generation.

**Table 11 Classification mean windspeeds [m/s]. The intervals are set to be 1m/s.**

| **Rating** | **Mean windspeed (m/s)** |
|---|---|
| 1 | 5 |
| 2 | 6 |
| 3 | 7 |
| 4 | 8 |
| 5 | 9 |
| 6 | 10 |
| 7 | 11 – 12 |
| NODATA | 0.11 – 4.999 |
| *NODATA* | *12.001 – 55* |

The boundaries set for this dataset are between than 5-12 m/s, as below 5 m/s there is little to no wind turbine generation and above 12 m/s are extreme windy places on earth and not taken into account for this project, as mentioned before. In the model rating 7 is actually 11 – 55 m/s but due to program errors this is must be done. Mean windspeeds higher than 12 m/s are considered as too high for the wind turbine system.

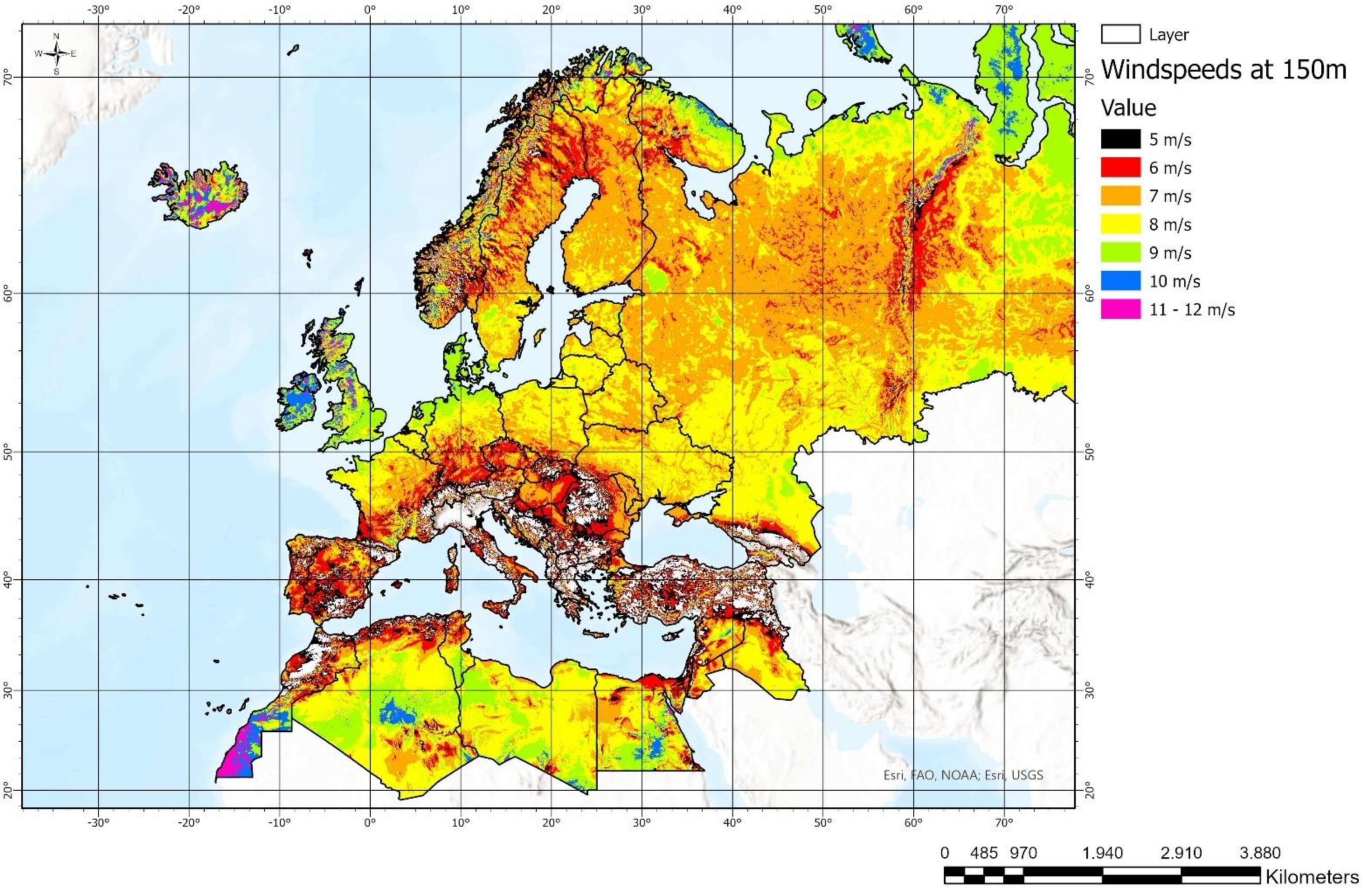


Figure 40 Reclassification of mean windspeeds. The highest interval is located in North-Europe and North-Africa.

Figure 40 shows the reclassified mean windspeed dataset. Areas in white, within the Country Boundaries, are not feasible for this research as the mean windspeed is lower than 5 m/s.

The population density and slope are classified the same way as for the solar scenario, shown in tables 7 and 8.

According to [21] the maximum slope used for a wind turbine is set at 10 degrees. In addition, the restricted areas airports have buffers set around them in the proximity of 10km as this is a safety measurement for hydrogen systems.

The datasets are then assigned a certain weight in a Weighted Sum tool to locate suitable areas. The weights are appointed to every layer to indicate a certain significance of the layer to the model. The mean windspeed is imperative to the model of locating suitable areas for a wind power generated green hydrogen electrolysis plant. Slope and population density have the same weight as the mean windspeed to only depict the areas with a certain slope and population density. This is shown in table 12 and the result is shown in figure 41.

**Table 12 Weighted sum of the wind criteria and each dataset has a weight of 1.**

| Criteria | Weight |
|---|---|
| Mean windspeeds | 1 |
| Slope | 1 |
| Population density | 1 |

The reclassified layers are then merged into a suitability map, excluding the restricted areas, with the final suitability scores per area ranging from 1 (low-windspeeds) to 7 (high windspeeds). To depict the layers separately, a raster calculator tool is used to calculate the potential of hydrogen production per area. These 7 areas are set to the final weighted sum score to extract the areas per mean windspeed class. This is shown in table 13.

**Table 13 Wind area number with mean windspeed class. The lowest mean windspeed interval has the lowest area number.**

| Rating | Wind Area number | Mean windspeed (m/s) |
|---|---|---|
| 1 | Area 1 | 5 |
| 2 | Area 2 | 6 |
| 3 | Area 3 | 7 |
| 4 | Area 4 | 8 |
| 5 | Area 5 | 9 |
| 6 | Area 6 | 10 |
| 7 | Area 7 | 11-12 |

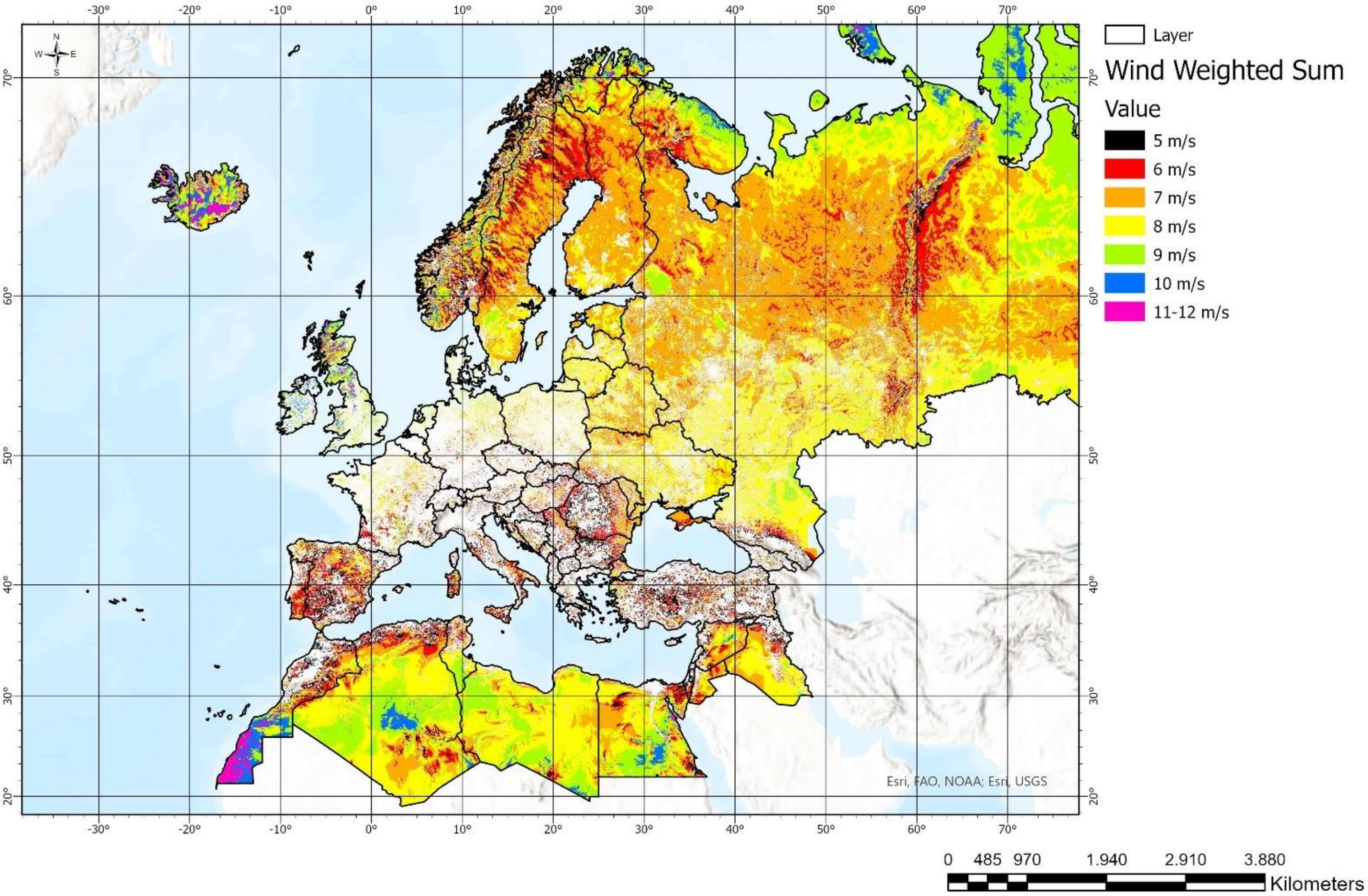


Figure 41 Wind mean windspeeds weighted sum. The amount of available area has decreased due to the slope and population density datasets.

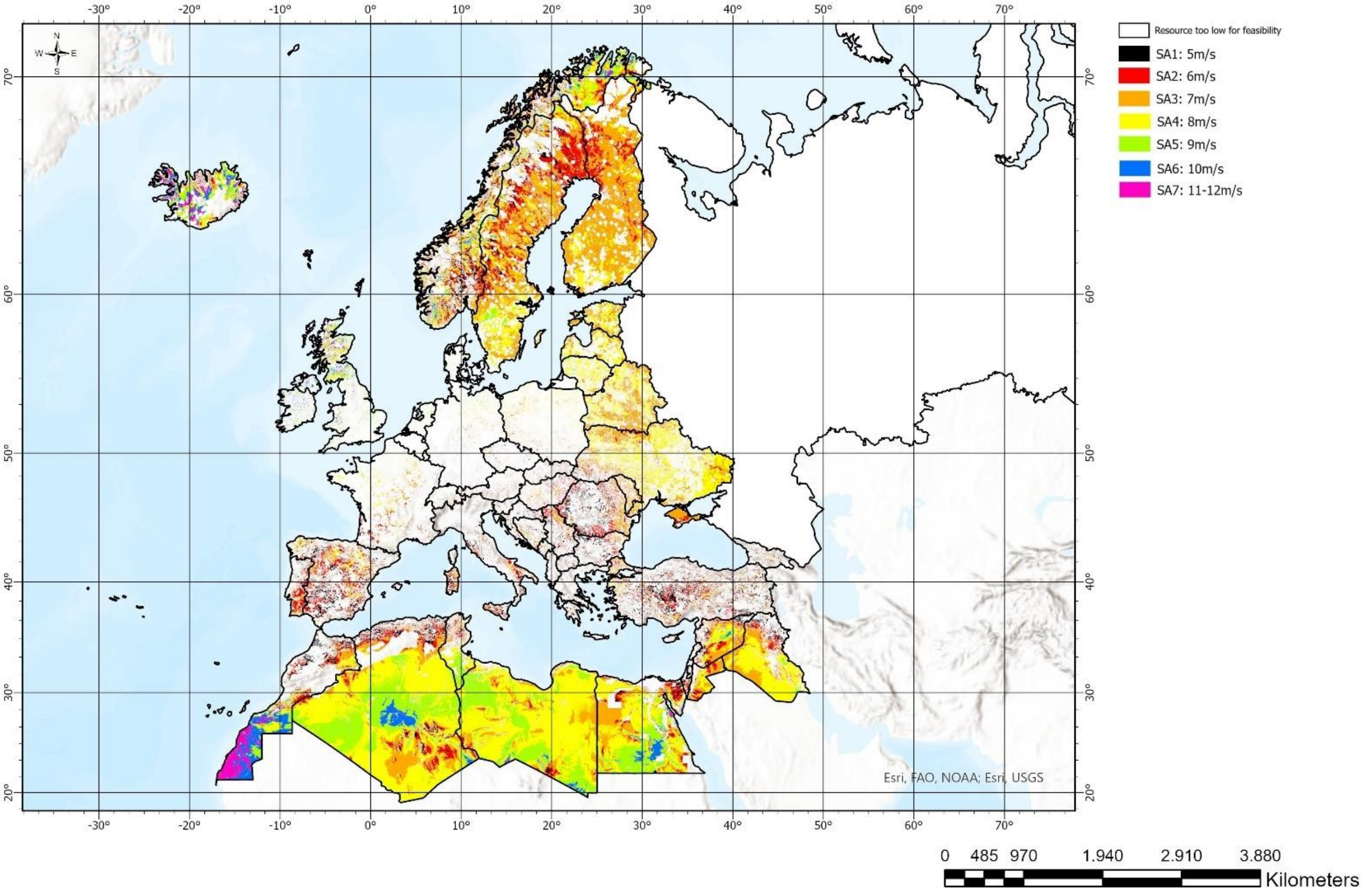


Figure 42 Suitability map wind scenario. The most suitable areas are located in North-Europe and North-Africa.

The final suitability raster is then put into polygon format for geometry calculations of all the areas in the datasets, shown in figure 42. This is needed to use the Select tool and filter the areas smaller than 1000km$^2$ from the suitability maps depicted in the Results chapter.

As in the solar scenario, to calculate the geometries of the areas per country a Clip tool is used to extract this from the final suitability map and is then used in the cost calculations model, shown in the financial modelling chapter.

### 2.3.5. SOLAR AND WIND COMBINATION SYSTEM SITE SUITABILITY

This scenario shows the modelling of only the solar panel potential power output and the mean windspeeds for hydrogen production. In addition, the same boundaries for both geospatial datasets are taken as explained in both previously mentioned scenarios.

The datasets selected for this scenario are mean windspeeds, solar power output potential, slope, population density, and the restriction areas, all mentioned in table

#### MODELING PROCESS

In table 14 the same rating for is kept as previous scenarios. Cross ratings e.g., areas with low power potential and high mean windspeeds and opposite have been calculated into one class but separation between which of the factors has a heavier weight in the calculation is not clear. This can be derived by looking at the solar power output potential and mean windspeeds maps seperately.

**Table 14 Classification of Power output potential and Mean windspeeds. This is the same classification is used for the solar and wind combination as for the solar and wind scenario.**

| Rating | Power output potential (kWh/kWp) | Mean windspeeds (m/s) |
|---|---|---|
| 1 | 800-1000 | 5 |
| 2 | 1000-1200 | 6 |
| 3 | 1200-1400 | 7 |
| 4 | 1400-1600 | 8 |
| 5 | 1600-1800 | 9 |
| 6 | 1800-2000 | 10 |
| 7 | 2000-2200 | 11-12 |
| NODATA | 0-799.99 | 0.11-4.99 |
| *NODATA in selected areas* | *2200-2470* | *12.001-55* |

The boundaries set for these datasets are also the same as the previous scenarios. The result of classifying these two datasets and overlaying them into one map is shown in figure 43.

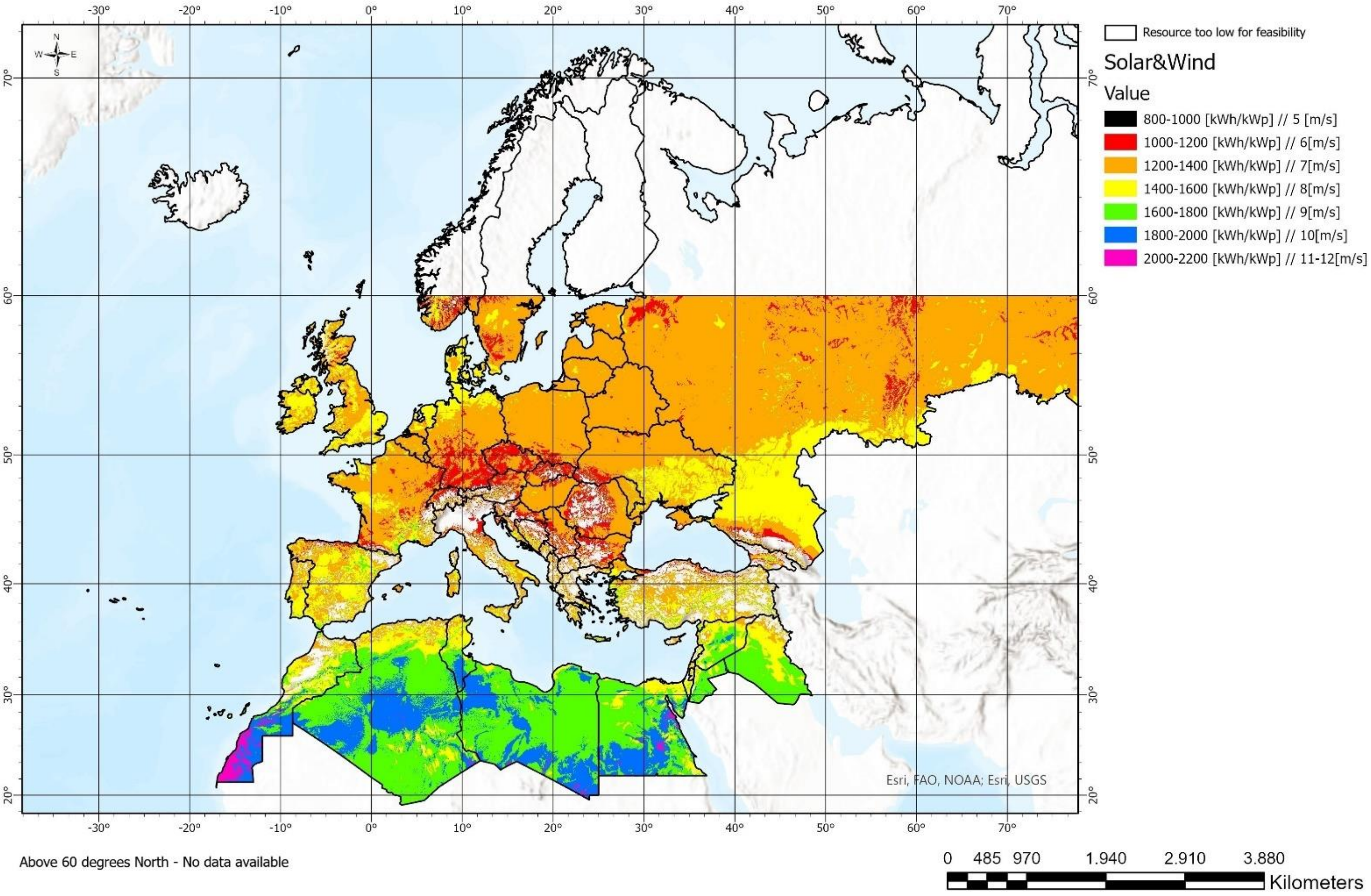


**Figure 43 Solar power output potential and mean windspeeds overlayed. The highest windspeeds overlayed with solar power output potential are located in North-Africa.**

The population density and slope are also modelled the same way as in the previous two scenarios. The results can be seen in tables 8 and 9.

The datasets are then assigned a certain weight in a Weighted Sum tool to locate suitable areas. The weights are appointed to every layer to indicate a certain significance of the layer to the model. The power potential output is imperative to the model of locating suitable areas for a solar power generated green hydrogen electrolysis plant. Slope and population density have the same weight as the power potential to only depict the areas with a certain slope and population density. This is shown in table 15.

**Table 15 Weighted sum Solar and Wind criteria and weights. All datasets have a weight of 1.**

| Criteria | Weight |
|---|---|
| Mean windspeeds | 1 |
| Slope | 1 |
| Population density | 1 |
| Solar power output potential | 1 |

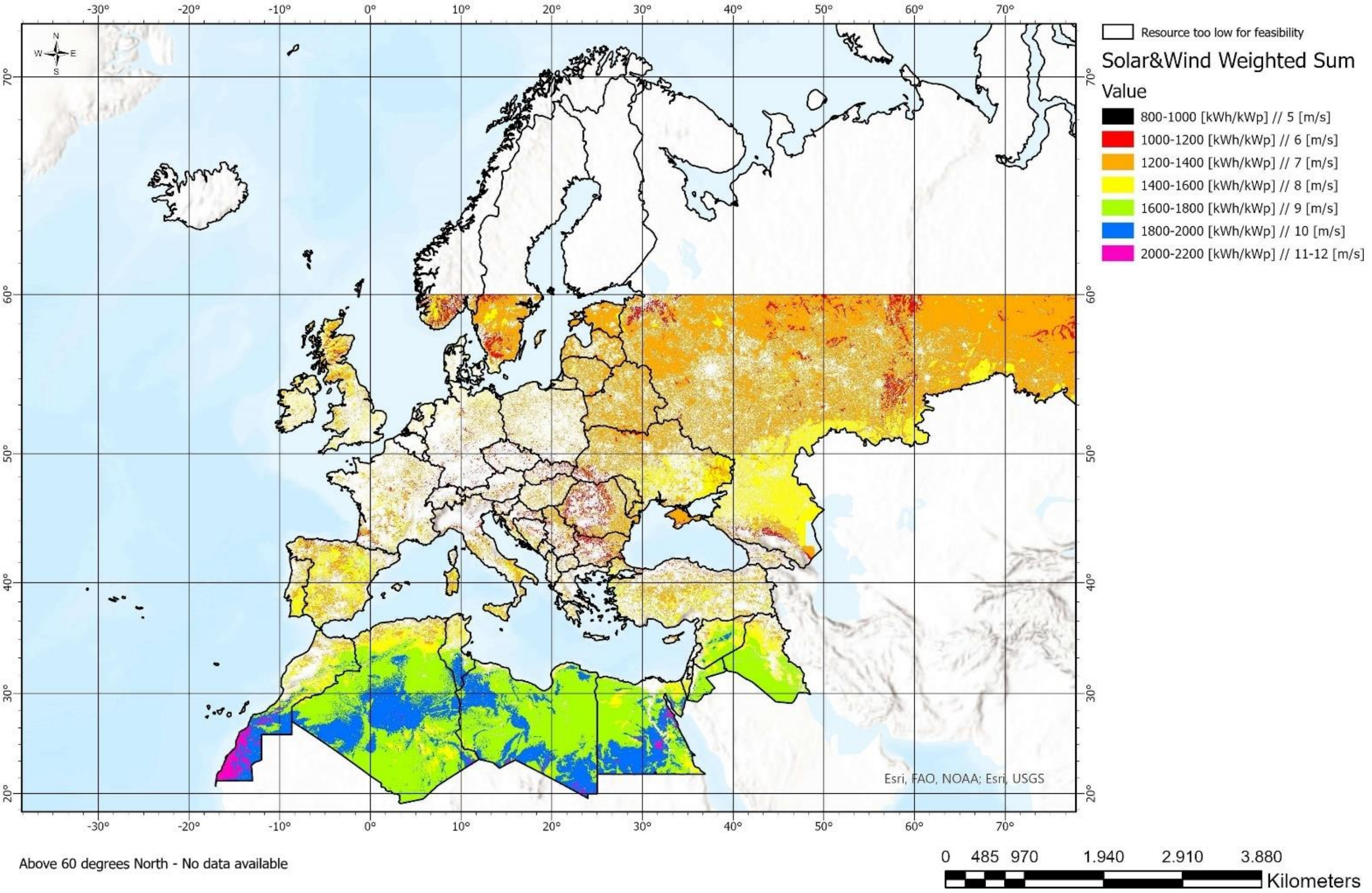


**Figure 44 Solar and Wind weighted sum. The amount of available area is reduced to the population density and slope datasets. The number of suitable areas reduces due to overlaying of the solar and wind datasets.**

The restricted areas are the same for each scenario and the results can be seen in figure 30. The merged reclassified layers are then merged into a suitability map, excluding the restricted areas, with the final suitability scores per area ranging from 1 (low-solar power potential output/ mean windspeeds) to 7 (high-solar power potential output/ mean windspeeds)), figure 44. To depict the layers separately a raster calculator tool is used to be able to calculate the potential of hydrogen production per area. These 7 areas are set to the final weighted sum score to extract the areas. This is shown in table 16.

**Table 16 Solar and Wind suitable area definition**

| Rating | Solar Wind Area | Power output potential (kWh/kWp) | Mean windspeed (m/s) |
|---|---|---|---|
| 1 | Area 1 | 800-1000 | 5 |
| 2 | Area 2 | 1000-1200 | 6 |
| 3 | Area 3 | 1200-1400 | 7 |
| 4 | Area 4 | 1400-1600 | 8 |
| 5 | Area 5 | 1600-1800 | 9 |
| 6 | Area 6 | 1800-2000 | 10 |
| 7 | Area 7 | 2000-2200 | 11-12 |

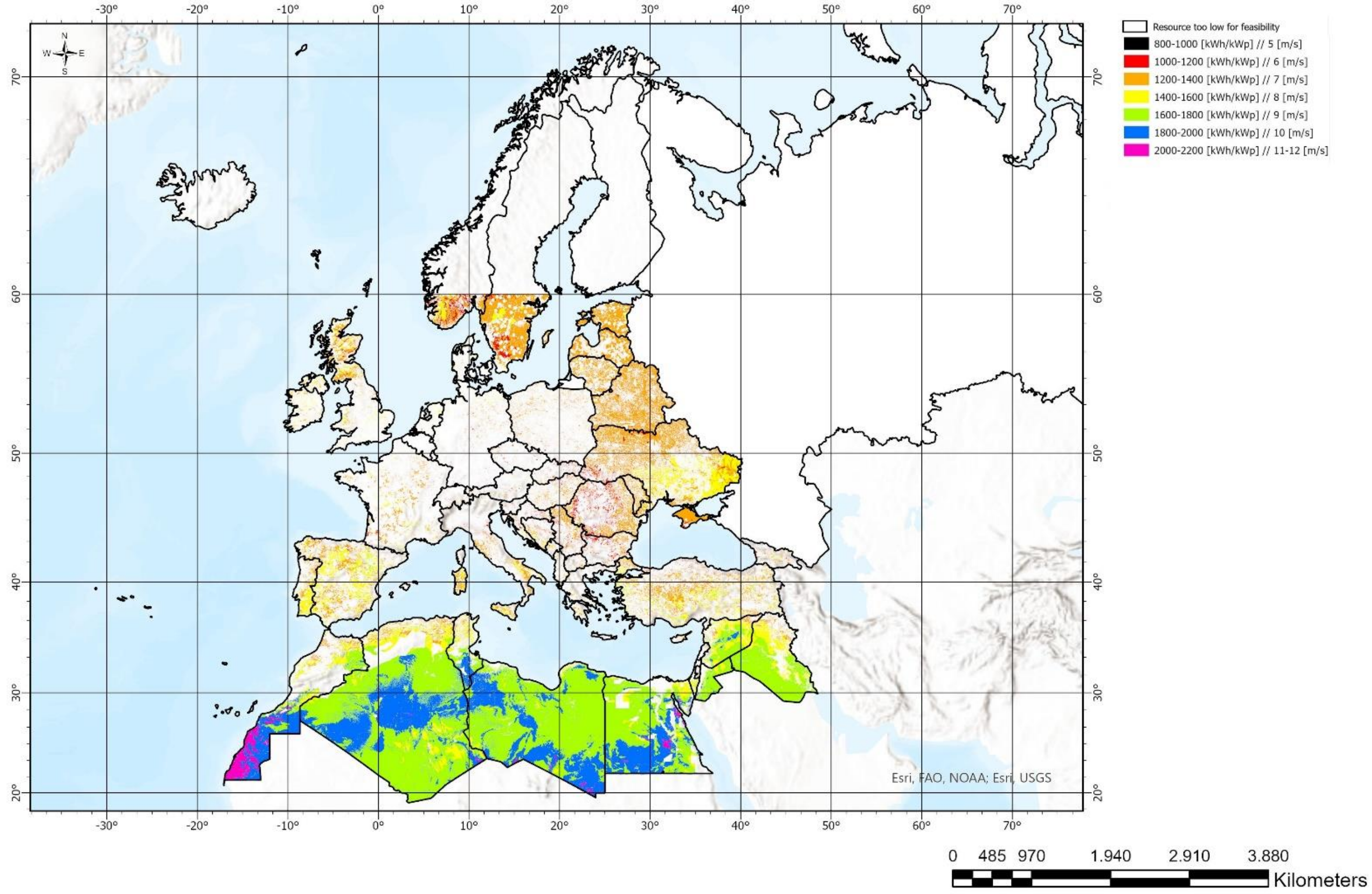


**Figure 45 Suitability map Solar and Wind scenario. The most suitable areas are located in North-Africa.**

The restricted areas are excluded from the reclassified geospatial raster datasets and the final suitability area in raster format is then shown, figure 45. The final suitability raster is then put into polygon format for geometry calculations of all the areas in the datasets. This is needed to use the Select tool and filter the areas smaller than 500km$^2$ from the suitability maps. This is because the solar scenario is limited to this area size and increasing the limit will only make the share of solar energy production larger, which will ultimately outweigh the wind energy production due to difference in land coverage. The final suitability map with size criterion and hydrogen prices is depicted in the Results chapter.

To calculate the geometries of the areas per country a Clip tool is used to extract this from the final suitability map and is then used in the cost calculations model, shown in the financial modelling chapter.

## 2.4 TECHNICAL HYDROGEN POTENTIAL

### 2.4.1. SOLAR PV SYSTEM YIELD

First, to calculate the total yield of the solar PV system the total installed power and the load hours per area needs to be determined. The installed power is the rated power of a solar PV panel multiplied by the number of PV systems installed, shown in equation 1.

$$Yield_S = C_S * FL_S \qquad (1)$$

$Yield_S$ = Yield solar system [kWh]

$C_S$ = Installed capacity solar PV system [kW]

$FL_S$ = Full load hours solar PV system [hours]

The PV power output potential is taken from a Photovoltaic power potential chart given by the Global Solar Atlas. Figure 46 depicts the kWh/kWp of different areas in Mediterranean region. The colour difference in the chart indicates the differences in areas in kWh/kWp, which are used to define the intervals used for this model. The same is done for Europe [15].

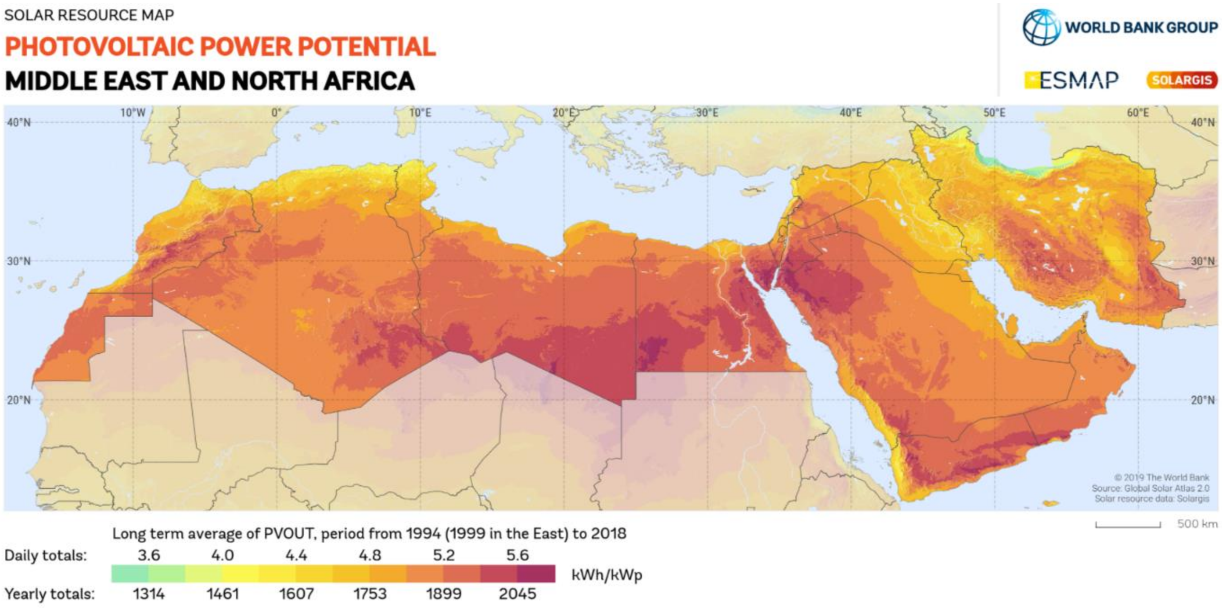


Figure 46 Power output potential heatmap in kWh/kWp of Mediterranean region [15]

To convert the power output potential into sun load hours figure 47 is used. The colour separations indicate the same layers as in figure 46 and can be used to depict the sun load hours per area [36].

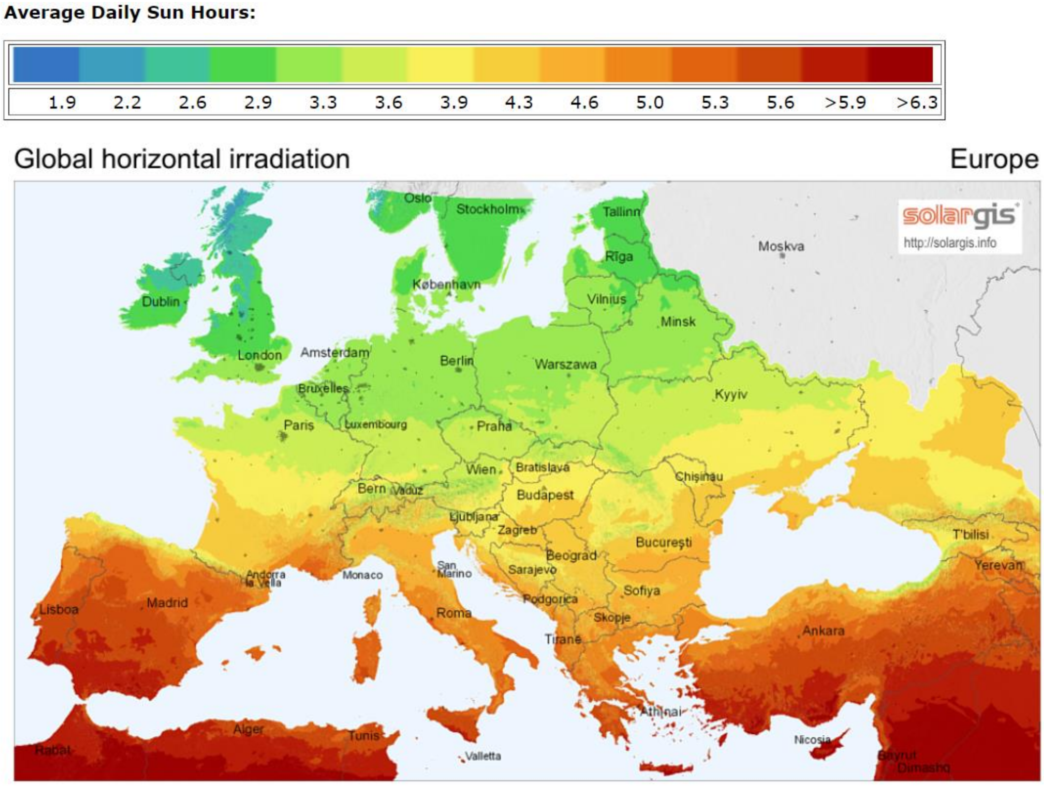


Figure 47 Average Daily Sun Hours for Global horizontal irradiation [36]

Then the total installed power must be determined to calculate the total yield of a solar farm per area, shown in equation 2. The number of PV systems is determined by the available area multiplied by the GCR and divided by the module size. Equation 3 shows how the number of PV systems is calculated.

$$C_S = P_{R\_S} * PV_n \quad (2)$$

$P_{R\_S}$ = Rated power solar system [kW]

$PV_n$ = Number of PV systems [-]

$$PV_n = \frac{(Area_A * GCR)}{(M_{size})} \quad (3)$$

$Area_A$ = Available area for solar PV system placement [m$^2$]

$M_{size}$ = Module size solar PV system [m$^2$]

To determine the total yield of a solar panel system, the ground coverage ratio, GCR, is needed. The GCR is the ratio of the module area to land area, shown in equation 4. This ratio needs to be determined to reduce shading losses [45].

$$GCR = \frac{L_{array}}{W_{Row}} \quad (4)$$

$L_{array}$ = Length of solar array [m]

$W_{Row}$ = Width of solar array row [m]

Then, to calculate the ground coverage ratio the row width must be known, which is dependent on the optimal tilt angle. Using equation 5 the row width is calculated.

$$W_{Row} = MRS_{ws} + \cos\left(\frac{T_s * \pi}{180}\right) * W_{array} \quad (5)$$

$MRS_{ws}$ = Minimum row spacing Winter Solstice [m]

$W_{array}$ = Width of solar array [m]

$T_s$ = Tilt angle solar panel [degrees]

Then, the azimuth correction angle must be used to get insight into the minimum row spacing during winter solstice. This is done by looking at figure 48 and using the 9 AM – 3PM line on the inside of the parabola to read the x-axis (Green line). The x-axis indicates the solar azimuth correction number. The solar azimuth correction number is determined by subtracting 180 degrees from the intersected point on the x-axis (Bottom side blue line).

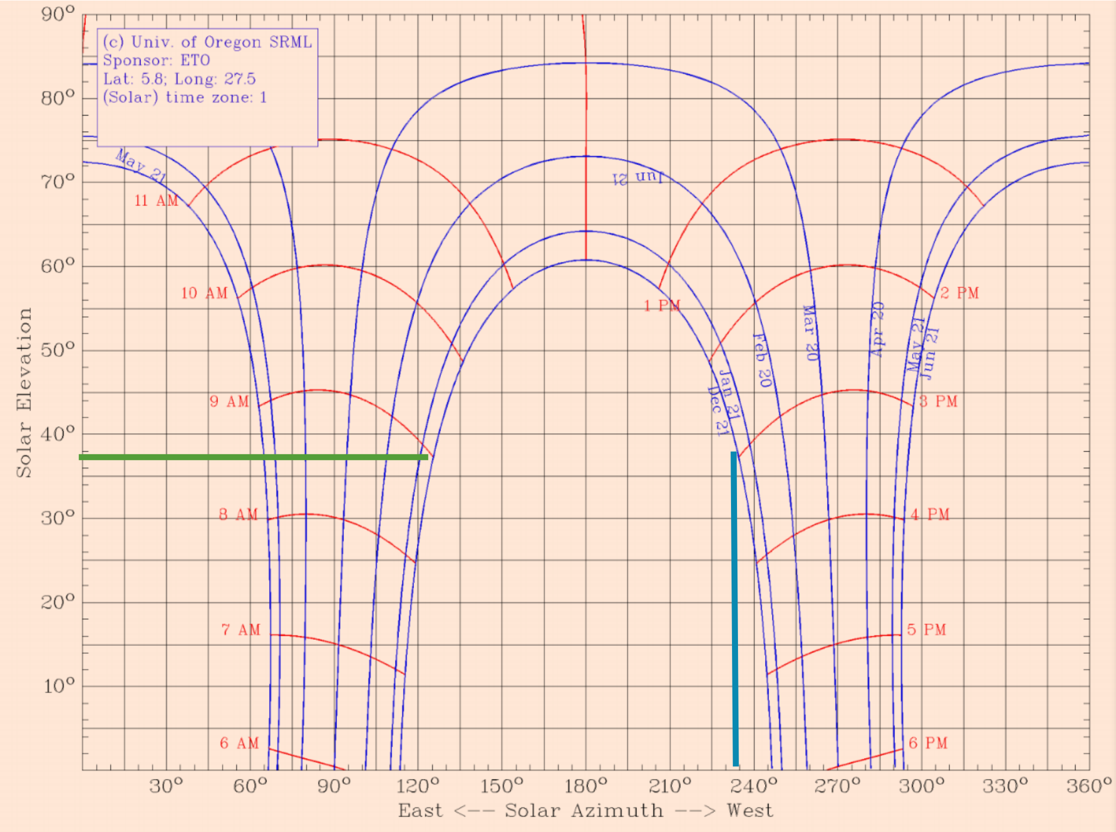


Figure 48 Winter Solstice Sun chart for Solar Azimuth and Solar elevation. The blue- and green line indicate the solar elevation and solar azimuth from 9AM – 3PM. This is needed to determine the minimum distance between solar arrays. [45]

Using equation 6 the minimum row spacing during winter solstice is calculated.

$$MRS_{ws} = \frac{S_{Mr}}{\cos\left(\frac{A_{ca}*\pi}{180}\right)} \quad (6)$$

$S_{Mr}$ = Spacing module row spacing [m]
$A_{ca}$ = Azimuth correction angle [degrees]

Then, the solar elevation angle is determined by looking at the winter solstice for the minimum distance needed between solar panel arrays. Figure 48 depicts a sun chart with the winter solstice of Lat: 5.8; Long: 27.5. Every area is taken on the same latitude but differing longitudes to create a realistic picture of every averaged optimal angle. The solar azimuth is set to 9 AM – 3 PM as this is a normal time for the sun to reach peak performance in the winter in Europe [45]. By looking at the y-axis (Blue line) the solar elevation angle can be read per area. Using equation 7 the module row spacing in meters is calculated.

$$S_{Mr} = \frac{Height\ difference}{\tan\left(\frac{SE_a * \pi}{180}\right)} \ (7)$$

$H_d$ = Height difference solar panel to ground [m]

$SE_a$ = Solar elevation angle [degrees]

The optimal angles in degrees for the placement of the solar PV array are depicted in figure 49. The angles are averaged and calculated in degrees. Because every area of solar power output potential is related to the average optimal PV panel angle, the ground coverage ratio is of influence on the hydrogen potential per area. Optimal angles increase with increasing distance of the location from the equator, meaning that the shadow of a solar panel array increases when the optimal angle increases. This ultimately to more space needed for the placement of such an array to reduce shadow losses. This dataset is divided into 7 classes to give this element the same rating as for the solar output potential. The solar power output potential shows the variation in solar irradiance between countries and provides information on the power potential between these countries.

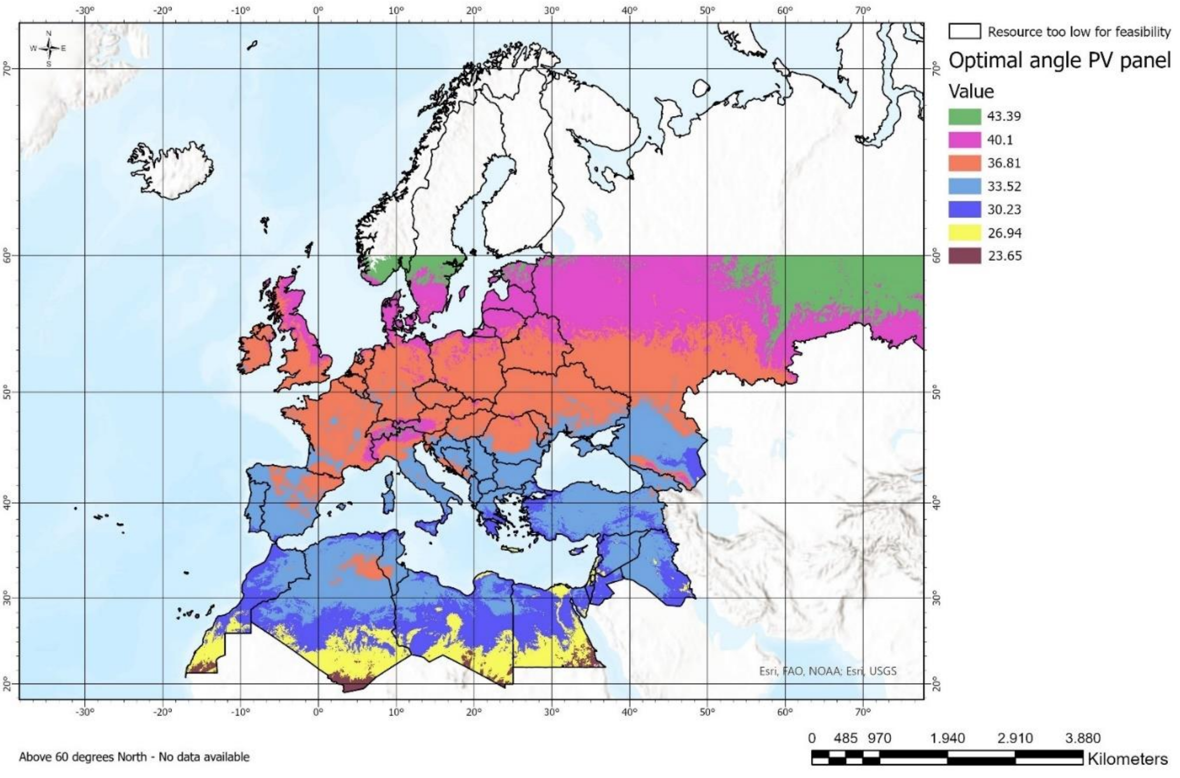


**Figure 49 Optimal PV panel tilt EU & Mediterranean region. The optimal angle decreases in regions on a lower latitude.**

The optimal angle for a PV panel is used as the tilt angle [15]. To calculate the GCR the height difference and solar elevation angle in degrees must be known. The height difference is calculated by using equation 8.

$$H_d = \sin\left(\frac{A_{opt} * \pi}{180}\right) * M_{pr} * L_{array} \qquad (8)$$

$A_{opt}$ = Optimal tilt angle [degrees]

$M_{pr}$ = Module per row [-]

$L_{array}$ = Length of solar array [m]

### 2.4.2. WIND TURBINE SYSTEM YIELD

The wind farm is assumed to have no obstruction near them. The surface friction, which influences wind power, is already considered in the mean wind speed data from Global Wind Atlas [25]. The yield of the windfarm is calculated by equation 9.

$$Yield_W = C_W * FL_W \quad (9)$$

$Yield_W$ = Yield wind turbine system [kWh]

$C_W$ = Installed capacity wind turbine system [kW]

$FL_W$ = Full load hours wind turbine system [hours]

The full load hours for the wind turbines are determined by first looking at the Annual Energy Production curve. This curve shows the annual production per mean wind speed for the 6 MW wind turbine, shown in figure 50.

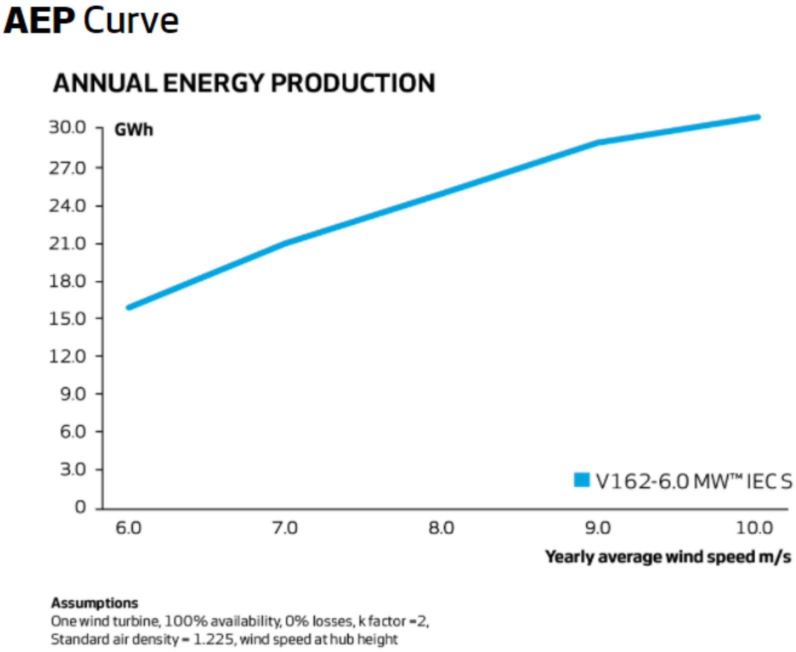


Figure 50 Annual Energy Production curve 6MW vestas wind turbine [47]

Figure 50 depicts the Annual Energy Production curve of a V164-6.0 MW IECS wind turbine. The annual energy production, on the y-axis, shows the amount of energy produced in GWh. The x-axis the mean windspeed correlating to the energy produced. Dividing the annual energy production by the wind turbine size gives the amount of load hours per mean windspeed class, shown in equation 10. Each windspeed class represents 1 out of 7 areas defined in the wind model, with Area 1 being 5 m/s and Area 7 being 11-12m/s.

$$FL_W = \frac{AEP}{P_{R\_W}}$$

$P_{R\_W}$ = Annual Energy Production [GWh]

The installed capacity of the windfarm is determined by the number of wind turbines used in the windfarm and the rated power per wind turbine. Equation 11 shows how the capacity is calculated.

$$C_W = P_{R\_W} * WT_n \text{ (11)}$$

$P_{R\_W}$ = Rated power wind system [kW]

$WT_n$ = Number of wind turbine [-]

The number of wind turbines needed for a certain area size is determined with equation 12. The available area and wind turbine spacing is needed for this equation.

$$WT_n = \frac{Area_A}{Sp^2} \text{ (12)}$$

$S_p$= Wind turbine spacing [$m^2$]

The spacing of a wind farm determines the total yield for a certain available area size. The spacing is dependent on the diameter of the rotor blades of the wind turbine. The spacing is needed for the wind turbines to work effectively with no uninterrupted flow of air [84]. The spacing of the wind turbine spacing is 6 times the rotor diameter, $D_R$ . Because the wind turbines in 2030 and 2040 have different sizes the rotor diameters are therefore also different. The spacing is determined by equation 13.

$$Sp = 6 * D_R \text{ (13)}$$

### 2.4.3. SOALR AND WIND COMBINATION YIELD

For the solar and wind hybrid scenario the yield is determined by the total yield of the solar and wind systems combined. Equation 14 includes a curtailment for the system. This curtailment is due to heat losses in the system.

$$Yield_{SW} = C * (Yield_{Solar} + Yield_{Wind}) \quad (14)$$

$C$ = Curtailment [% of yield loss]

## 2.5 ECONOMIC HYDROGEN POTENTIAL

In this section, an overview of the different components that contribute to the production price of hydrogen are shown. To calculate the price of green hydrogen production an economic model is developed that is assumed to be a proxy for the measure for future market prices of green hydrogen.

For the calculation of the Levelized Cost of Hydrogen the following factors are determining; Lifetime, capex, opex, electricity price and electrolyzer efficiency. The calculations are based on the concept of Levelized costs [80]. This cost model is adapted from [79]. Furthermore, all cost factors are in Euro without any inflation considered. The cost factors are based on current forecasted costs for 2030 and 2040.

The levelized cost of hydrogen is determined by the price per unit of energy used to produce hydrogen and the investment costs per unit hydrogen, shown in equation 15.

$$LCOH = \frac{AF*CAPEX_E+OPEX_E+EF*LCOE*H2PROD}{H2PROD} \quad (15)$$

LCOH = Levelized cost of hydrogen production [€/kg]

$CAPEX_E$ = Investment cost electrolyzer system [€/kW]

AF = Annuity Factor [-]

$OPEX_E$ = O&M cost electrolyzer system [% of CAPEX]

EF = Efficiency electrolyzer [kWh/kg*H2]

LCOE = Levelized cost of electricity [€/kWh]

H2PROD = Hydrogen Production per year [kg]

The annuity factor is calculated in equation 16. It is used to enable for the cost factors to adjust for different lifetimes e.g., the investment costs. The Weighted Average Cost of Capital, *WACC*, is needed in this equation to determine if the return in the different lifetimes, *n*, exceeds or meets the investment costs and to maximize these potential investments for the project. This number varies per country and year, as explained in the next sub-chapter.

$$AF = \frac{(1+WACC)^n*WACC}{(1+WACC)^n-1} \quad (16)$$

WACC = Weighted Average Cost of Capital [%]

n = lifetime (years)

Next, the amount of produced hydrogen is calculated in equation 17. This is done by taking the total yield of the renewable energy system and dividing it by the efficiency of the electrolyzer. The efficiency of the electrolyzer is determined by how much energy is needed to produce 1 kilogram of hydrogen.

$$H2PROD = \frac{Yield_{RE\,system}}{EF} \quad (17)$$

$Yield_{RE\,system}$ = Yield renewable energy system per year [kWh]

EF = Efficiency electrolyzer [kWh/kg*H2]

The LCOE in equation 5 is the LCOE of solar or wind or a combination of solar and wind. The levelized cost of electricity is determined by the total size and annual cost of the renewable energy system divided by its total annual yield.

$$LCOE_{Solar} = \frac{C_S * AF * CAPEX_S + OPEX_S}{EProd_S} \quad (18)$$

$LCOE_{Solar}$ = Levelized cost of electricity production by solar [€/kWh]

$CAPEX_S$ = Investment cost solar PV system [€/kW]

$OPEX_S$ = O&M cost solar PV system per year [% of $CAPEX_S$]

$C_S$ = Installed capacity solar PV system [kW]

The total electricity produced is set equal to the amount of full load hours, seen in equation 5. The full load hours differ per area and determine the amount of available energy source for the renewable energy system.

$$EProd_S = Yield_S \quad (19)$$

$EProd_S$ = Electricity production solar per year [kWh/kW]

Equation 20 and 21 show the LCOE for wind energy.

$$LCOE_{Wind} = \frac{C_W * AF * CAPEX_W + OPEX_W}{EProd_W} \text{ (20)}$$

$LCOE_{Wind}$ = Levelized cost of electricity production by wind [€/kWh]

$CAPEX_W$ = Investment Cost wind turbine system [€/kW]

$OPEX_W$ = O&M cost wind turbine system per year [% of $CAPEX_S$]

$C_W$ = Installed capacity wind turbine system [kW]

$$EProd_W = Yield_W \text{ (21)}$$

$EProd_W$ = Electricity production wind per year [kWh/kW]

Equation 22 shows how the LCOE for the solar and wind combination is determined. This LCOE is dependent on the LCOE and total yield of wind and solar individually. By dividing this number by the total yield, the average LCOE for the solar and wind combination per area is determined.

$$LCOE_{Solar\&Wind} = \frac{Yield_S * LCOE_{Solar} + Yield_W * LCOE_{Wind}}{Yield_{Solar+Wind}} \text{ (22)}$$

$LCOE_{Solar\&Wind}$ = Levelized cost of electricity production by solar and wind [€/kWh]

$Yield_S$ = Yield solar PV system [kWh]

$Yield_W$ = Yield wind turbine system [kWh]

Equation 23 shows the total hydrogen production of the solar and wind combination. Dividing the full load hours of this hybrid system by the efficiency of the electrolyzer determines the total production of a specific area.

$$H2PROD_{SW} = \frac{FL_{SW}}{EF} \text{ (23)}$$

$FL_{SW}$ = Full load hours wind and solar system [hours]

The full load hours of this system are determined by the total yield and the capacity of the electrolyzer. This is shown in equation 24.

$$FL_W = \frac{Yield_{SW}}{C_E} \quad (24)$$

$C_E$ = Capacity electrolyzer [kW]

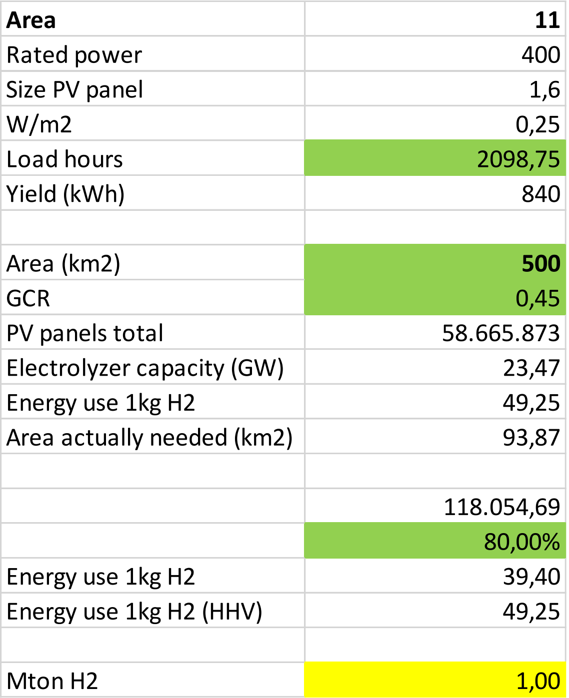
The capacity of the electrolyzer is oversized by 2 to accommodate for the system size of the wind and solar combination, shown in equation 25 [51].

$$C_E = 0.5 * (\ C_S + C_W) \quad (25)$$

## 2.6 ELECTROLYZER- AND AREA SIZE FOR 1 MILLION TONS OF GREEN HYDROGEN PRODUCTION

For this sub-chapter an excel model is made to calculate the potential hydrogen production per 500 km$^2$ and the actual needed area size for a production of 1 Mton per area for the solar-, wind-, and the solar and wind hybrid scenario. 500 km$^2$ is seen as a starting point for the calculations of the actual size needed for a production of 1 million tons of hydrogen. In addition, with the latter information the electrolyzer size for a production of 1 Mton of hydrogen can be calculated in the same model.

By knowing the total produced amount of hydrogen per 500km$^2$ for area 1-7, excel allows to back calculate the result and keep the final amount at 1 million tons. The final area size used for this amount per area can be retrieved with the Solver-function [97]. An example calculation is shown in figure 51.



| | |
|---|---|
| **Area** | **11** |
| Rated power | 400 |
| Size PV panel | 1,6 |
| W/m2 | 0,25 |
| Load hours | 2098,75 |
| Yield (kWh) | 840 |
| | |
| Area (km2) | **500** |
| GCR | 0,45 |
| PV panels total | 58.665.873 |
| Electrolyzer capacity (GW) | 23,47 |
| Energy use 1kg H2 | 49,25 |
| Area actually needed (km2) | 93,87 |
| | |
| | 118.054,69 |
| | 80,00% |
| Energy use 1kg H2 | 39,40 |
| Energy use 1kg H2 (HHV) | 49,25 |
| | |
| Mton H2 | 1,00 |

Figure 51 Example calculation of needed area size and electrolyzer capacity for 1 million tons of hydrogen The Mton is back calculated with the Solver-function in excel.

The total produced green hydrogen (yellow) is kept at 1 Mton and the area actually needed is recalculated by the Solver-function. This done while adjusting the PV panels total to the required number of panels needed to produce 1 million tons. This automatically changes the electrolyzer capacity as the amount of PV panels total affects the capacity of the installed capacity of the solar farm. The results per area are shown in the Results chapter.

## 2.7 INPUT DATA

### 2.7.1. GEOGRAPHICAL HYDROGEN POTENTIAL

These criteria are found to be the most suitable criteria for the scale of this research. Similar research on GIS-based site suitability for solar farms shows that the main criteria are solar irradiation, physical suitability, cost-effectiveness, and land availability [22][92][93]. For this research only solar irradiation and physical suitability criteria are considered due to the size of the scope. The same can be said for wind turbine criteria and therefore only mean wind speeds and physical criteria such as slope are considered for this research [75][94]. Including more criteria will specify the findings but that is left for more detailed research in the future. These criteria, shown in table 17, together comprise the suitability of areas for the potential of solar energy in Europe and Mediterranean region.

**Table 17 Criteria Solar scenario with reason for selection, data source, original data structure and feature type**

| Criteria | Reason for selection | Data source | Original data structure | Feature type |
|---|---|---|---|---|
| Solar power output potential | Essential for solar power production | Global Solar Atlas [15] | Vector | Polygon |
| Slope | Effect on construction and maintenance | The World Bank [16] | Vector | Polygon |
| Population density | Essential safety, visual and noise impact | EEA [17] | Vector | Polygon |
| Mean windspeed at 150m | Essential for wind power production | Global Wind Atlas [25] | Vector | Polygon |
| **Exclusionary areas** | | | | |
| Airports | Avoiding areas near airports | Eurostat [18] | Vector | Polygon |

|  |  |  |  |  |
|---|---|---|---|---|
| Cities | Avoiding areas near cities | NYU Spatial Data [19] | Vector | Polygon |
| Areas of natural beauty | Conflicting use of land areas | ArcGIS [20] | Vector | Polygon |

## SOLAR POWER OUTPUT POTENTIAL

Table 18 shows the load hours per area derived from figure 47. The conversion of the power output potential to average daily sun hours is shown. The intervals for the power output potential are set to 200 kWh/kWp and start from 800 kWh/kWp. Using 200 kWh/kWp for the interval shows to give a detailed enough representation of the solar irradiance to give a realistic hydrogen price per region at the end.

**Table 18 Average Load Hours per year per power output potential class**

| ***kWh/kWp interval*** | ***Area number*** | ***LH/day (min)*** | ***LH/day (max)*** | ***LH/year (min)*** | ***LH/year (max)*** | ***LH/year average*** |
|---|---|---|---|---|---|---|
| *800-1000* | *1* | *2.3* | *2.8* | *839.5* | *1022* | *930.75* |
| *1000-1200* | *2* | *2.8* | *3.5* | *1022* | *1277.5* | *1149.75* |
| *1200-1400* | *3* | *3.5* | *4* | *1277.5* | *1460* | *1368.75* |
| *1400-1600* | *4* | *4* | *4.5* | *1460* | *1642.5* | *1551.25* |
| *1600-1800* | *5* | *4.5* | *5* | *1642.5* | *1825* | *1733.75* |
| *1800-2000* | *6* | *5* | *5.5* | *1825* | *2007.5* | *1916.25* |
| *2000-2200* | *7* | *5.5* | *6* | *2007.5* | *2190* | *2098.75* |

Figure 52 shows the load hours vs. the solar power output potential in a graph. The x-axis shows the power output potential in 7 classes. These numbers are averaged for each class for simplicity. The y-axis shows the load hours per class solar power output potential. The linear line depicts the load hours used for the calculations in this research to determine the yield of the solar PV system. The line is linear since the solar power output potential dataset is divided into 7 classes with the same interval.

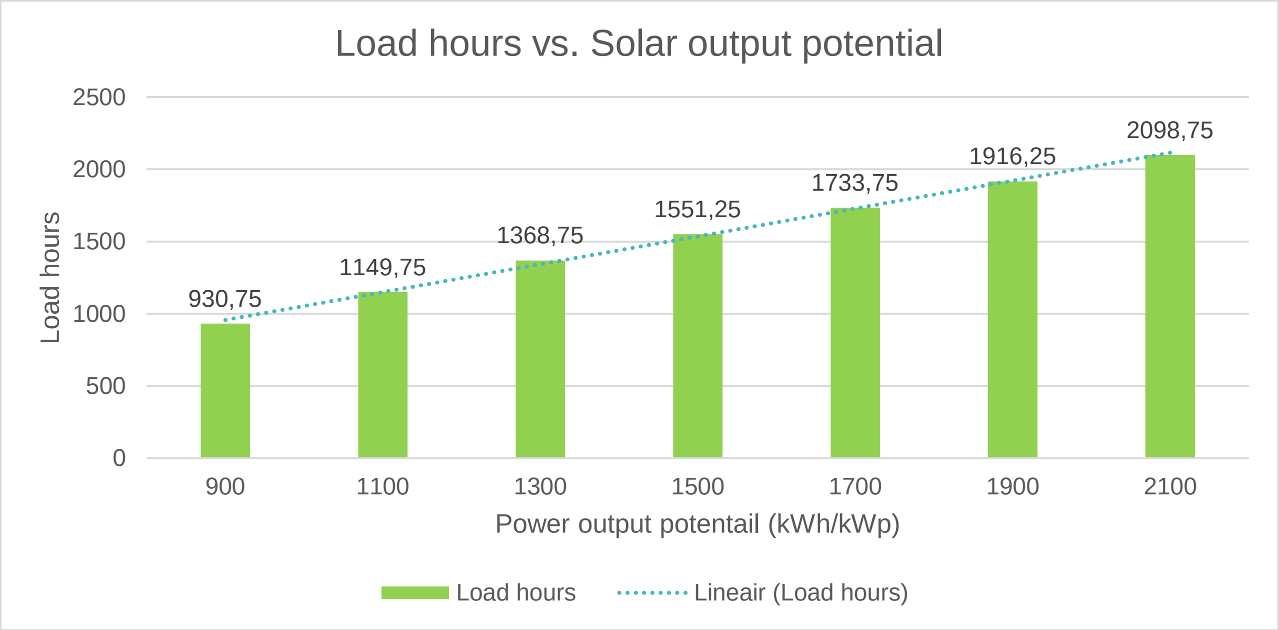


Figure 52 Load hours vs. power output potential solar PV panel

## MEAN WIND SPEEDS

Table 19 shows the mean windspeeds and load hours per area. The load hours are estimated to be 10% higher in 2040 due to the increase in efficiency of the wind turbine system [104].

**Table 19 Mean windspeed with corresponding Load Hours. In 2040 the load hours are estimated to be 10% higher due to higher efficiency in the wind turbine.**

| Area | Mean Windspeed (m/s) | Load Hours 2030 | Load hours 2040 |
|---|---|---|---|
| 7 | 11-12 | 5250 | 5775 |
| 6 | 10 | 5000 | 5500 |
| 5 | 9 | 4667 | 5133.7 |
| 4 | 8 | 4000 | 4400 |
| 3 | 7 | 3500 | 3850 |
| 2 | 6 | 2667 | 2933.7 |
| 1 | 5 | 2000 | 2200 |

Figure 53 shows the load hours vs. mean wind speed in a graph for 2030 and 2040. The x-axis shows the power output potential in 7 classes. These numbers are averaged for each class for simplicity. The y-axis shows the load hours per class solar power output potential. It is assumed that the 10MW wind turbine for the 2040 scenario makes more efficient use of the available wind power, which increases the average load hours per class.

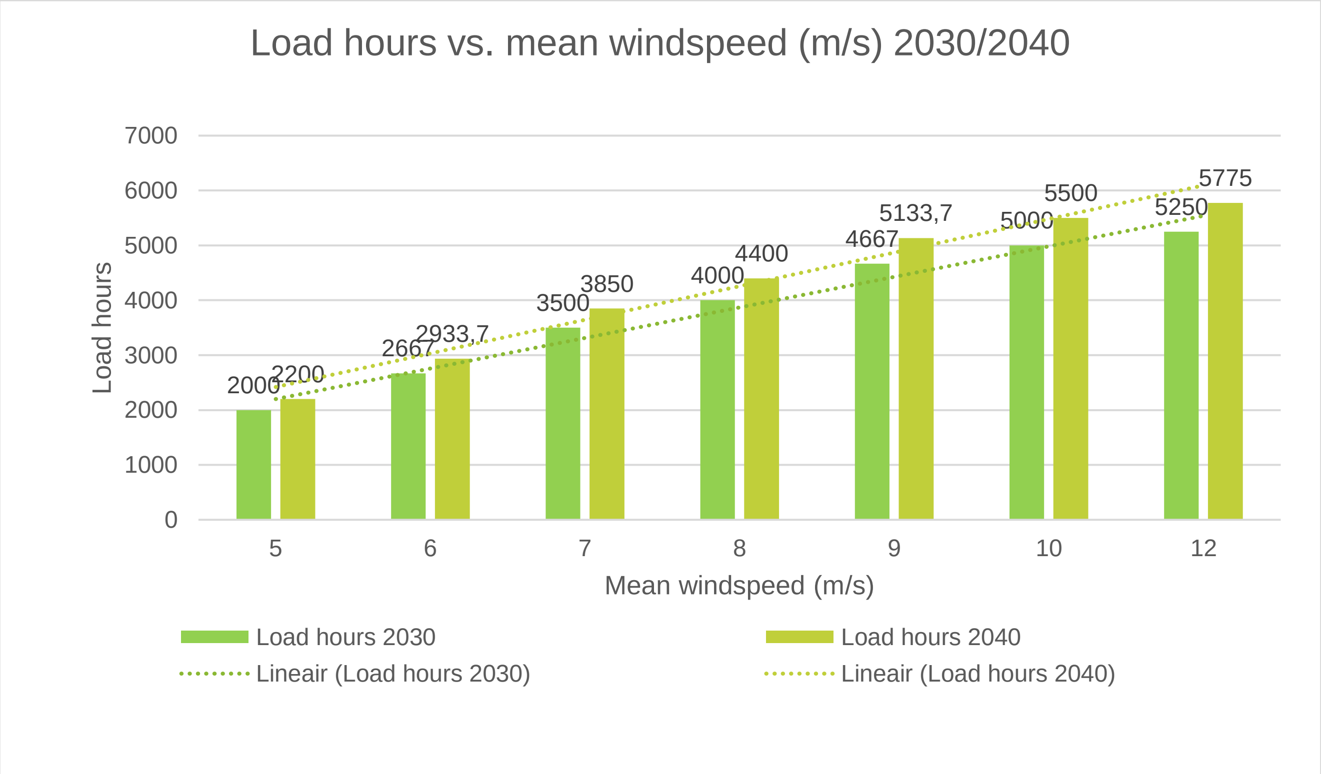


**Figure 53 Load hours vs. mean windspeed for 2030 and 2040**

## 2.7.2. TECHNICAL HYDROGEN POTENTIAL

### ELECTROLYZER EFFICIENCY

Table 20 depicts the electrolyzer efficiency in 2030 and 2040.

**Table 20 Input variables electrolyzer in 2030 and 2040**

| Input | Value 2030 | Value 2040 |
|---|---|---|
| Efficiency electrolyzer (HHV) [%] | 80 | 85 |

The system efficiency (HHV) for 2030 is set to 80% and 85% for 2040 as an assumption based on the learning curve of this technology [7][63].

Table 21 depicts the rated power, and power per area for the solar PV system in 2030 and 2040.

**Table 21 Input variables solar PV panel in 2030 and 2040**

| Input | 2030 | 2040 |
|---|---|---|
| Rated power [kWp] | 0.4 | 0.45 |
| kWp/m$^2$ | 0.25 | 0.28 |

The average rated power for a solar PV panel in 2021 is around 300 Wp [42]. For this research learning rate of 25% between 2020 and 2030 of solar PV  is considered [7]. This results in a rated power of 400 Wp in 2030. For 2040 there is little information provided to what extent the learning rate is between 2030 and 2040. For this scenario an averaged rated power for a solar PV panel of 450 Wp is considered.

The power per area for the solar PV panel is the ratio between solar PV panel size and the rated power, which indicates the amount of power one PV panel can produce per m$^2$. This is needed to calculate the total yield per available area.

For the GCR the following input variables are used. The first parameters to be defined are the solar panel PV input variables shown in table 22. According to [44], the optimal solar panel array placement is 3 panels in a landscape profile, which is used for this research. The module length and width are the standard measurements of a single PV panel [90].

**Table 22 Input variables for Ground Coverage Ratio**

| Input variables | Value |
|---|---|
| Module Length [m] | 1 |
| Module width [m] | 1.6 |
| Module per row [-] | 3 |
| Array length [m] | 3 |
| Array width [m] | 4.8 |

The input variables for the ground coverage ratio are shown in table 23. The optimal tilt angle is determined from figure 50. Columns 3-8 are intermediate results from equations 4 – 8. These intermediate results are used as input data for the calculation of the yield for the solar PV system.

**Table 23 Intermediate results for the Ground Coverage Ratio**

| Area | Optimal tilt angle | Height difference | Solar elevation angle | Module row | Azimuth correction angle | Min. row spacing | Row width | Ground Coverage Ratio |
|---|---|---|---|---|---|---|---|---|
| 7 | 23.65 | 3.61 | 38 | 4.6 | 61 | 2.2 | 6.6 | 0.45 |
| 6 | 26.94 | 4.08 | 37 | 5.4 | 60 | 2.7 | 7.0 | 0.43 |
| 5 | 30.23 | 4.53 | 37 | 6.0 | 59 | 3.1 | 7.2 | 0.41 |
| 4 | 33.52 | 4.97 | 37 | 6.6 | 58 | 3.5 | 7.5 | 0.40 |
| 3 | 36.81 | 5.39 | 37 | 7.2 | 55 | 4.1 | 7.9 | 0.38 |
| 2 | 40.1 | 5.80 | 35 | 8.3 | 54 | 4.9 | 8.5 | 0.35 |
| 1 | 43.39 | 6.18 | 35 | 8.8 | 53 | 5.3 | 8.8 | 0.34 |

Table 24 depicts the rated power, and power per area for the solar PV system in 2030 and 2040.

Table 24 Input variables wind turbine in 2030 and 2040

| **Input** | **2030** | **2040** |
|---|---|---|
| Rated power [MW] | 6 | 10 |
| Rotor Diameter [m] | 164 | 192 |
| MW/km$^2$ | 6.35 | 7.46 |

The rated power of the wind turbine is taken at 6MW, which is assumed to be the average rated power of a wind turbine in 2030 [47]. For 2040 the rated power is assumed to be 10MW for an onshore wind turbine [46]. As mentioned in the list of assumption, the specifications for both wind turbines are taken from.

The power per area size is determined by the yield and spacing. The spacing is determined by the rotor diameter of the wind turbines. For 2030 and 2040 different wind turbine sizes are used with different rotor diameters. The rotor diameter of the 6 MW wind turbine is 162 m [47] and the 10 MW wind turbine 192 m [46].

Table 25 depicts the oversizing ratio and curtailment of the solar and wind combination system.

Table 25 Input variables solar and wind combination in 2030 and 2040

| Input | 2030 | 2040 |
|---|---|---|
| Oversizing electrolyzer for solar and wind systems [-] | 2 | 2 |
| Curtailment [%] | 10 | 10 |

Because this system is a stand-alone system the intermittency and variability of solar and wind farms causes concern of how to operate electrolyzer reliably, economically, and sustainably by using solely renewable energy sources. A suggestion made by [92] is to oversize the system to enhance operational capacity  factors and achieve more economical operation of the electrolyzer. Oversizing the system by 1.5 times is the most ideal when looking at energy prices, shown in figure 54.

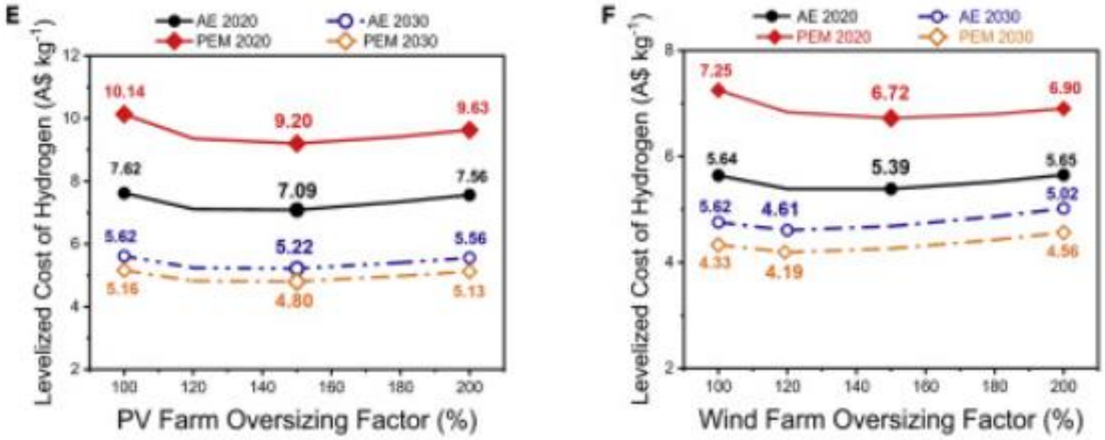


Figure 54 PV farm and wind farm oversizing ratio shows that the most ideal ratio is 1.5 [92]

For this research the system is oversized by 2 due to the large capacity factors in the most optimal areas, especially for the wind scenario in 2040. In addition, an oversizing of 2 considers the additional load provided by surplus energy produced. Also, [92] considers a MW-scale green hydrogen system and remarks the increase in oversizing the system when larger scales are used.

In addition, a curtailment of 10% is estimated for heat losses to adjust the system to the electrolyzer [10].

## WACC

The WACC, weighted average cost of capital, is a direct and indirect measurement of how the return rate of capital required is impacted [55]. Renewable energy technologies are more capital intensive than their fossil fuel counterparts, which results in the LCOH being sensitive to the WACC. A representable WACC for Europe and the North-African countries would be around 6% [31][85], as shown in figure 31. Research suggest that using a homogenous WACC for Europe is beneficial for market growth as the discount rate differs per country, seen in figure 55 for solar and wind technology. An inhomogeneous model shows that WACC rates for renewable energy resources are lower in developed countries than under-developed countries [86], also seen in figure 30. For this research the WACC is set at a constant number, 6%, for simplicity. In the discussions chapter the WACC is further discussed. Figure 55 show the WACC for solar PV and wind turbine technology, which differs per country and year.

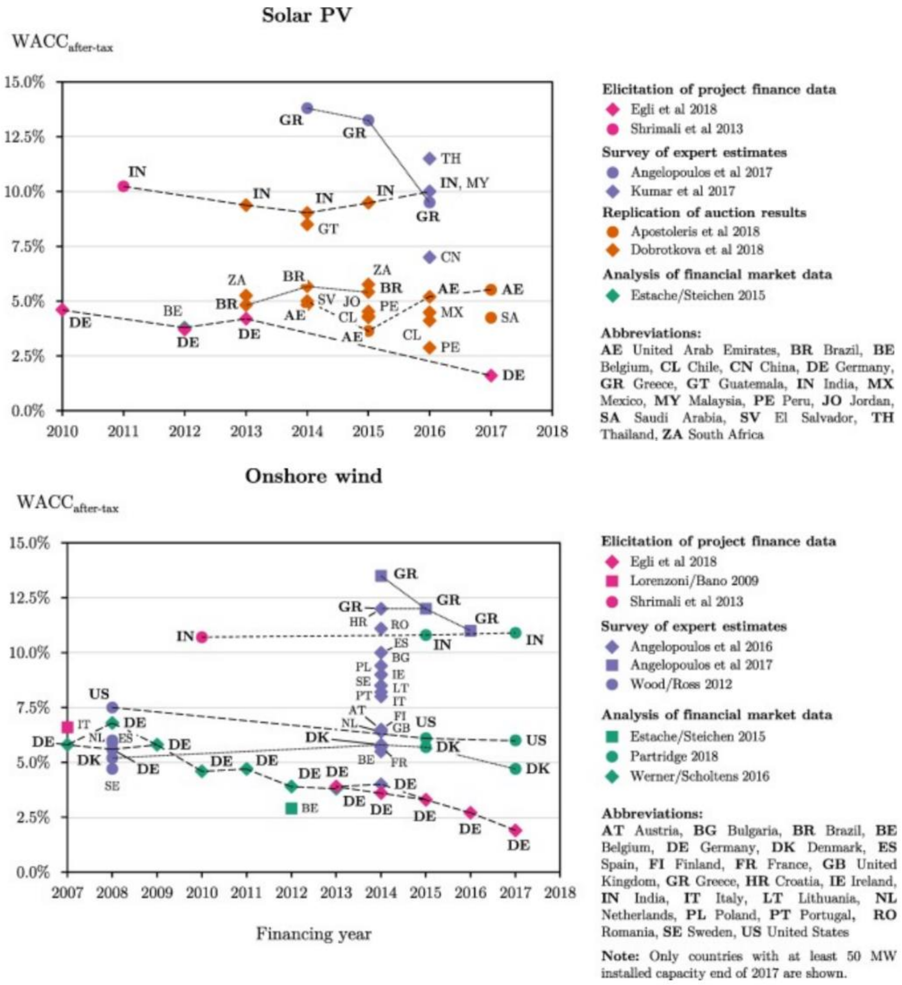


**Figure 55 WACC of Solar PV and Onshore technology of different countries between 2007 – 2018 [31]**

## OPEX

For this research an opex of 1% is considered. The operational expenditure, opex, for solar PV panels, wind turbines and the electrolyzer cost calculations has been set to 1%. Looking at assumptions made for large scale hydrogen projects for 2030 and onwards [63][86] shows that the opex is around 1-1.5% for 2030. [86] even implies that the opex for electrolyzer technology will be under 1% between 2030 and 2050. [30] shows that large scale hydrogen projects differ between 1-3%, depending on scale.

## THE CAPEX OF THE SOLAR PV SYSTEM

Table 26 depicts the lifetime, and the capex of the solar PV system in 2030 and 2040.

**Table 26 Input variables solar PV panel in 2030 and 2040**

| **Input** | **2030** | **2040** |
|---|---|---|
| CAPEX [€/kW] | 500 – 300 | 417 – 250 |
| Lifetime [yr] | 20 | 20 |

The capex is calculated by taking two known capex numbers in areas between the intervals of 800-2200 kWh/kWp. Then the capex is distributed dynamically between these two checkpoints to create a realistic view of the capex in 2030 and 2040, as cost vary between areas of high and low amount of solar irradiance [86]. According to [38] [39] [40] the capex can be estimated to be between 300-500 €/kW in 2030, with 300 €/kW for areas with 1800 load hours and 500 €/kW for areas with 930 load hours. It is assumed that the costs in 2040 vary between 250-417 €/kW, depicted in table 26 [40]. The capex for 2040 is a function of the capex in 2030. The capex of area 7 are taken as ratio (300:250) and multiplied by the capex in 2030 of a new area, shown in equation 27, which implies the percentage change of capex between areas in 2030 and 2040 [91].

$$Capex_{2040} = \frac{Capex_{Area7\ 2040}}{Capex_{Area7\ 2030}} * Capex_{Area\ X\ 2030} \quad (26)$$

Table 27 Capex range for solar PV panels in 2030 and 2040

| Area (2030) | €/kW (2030) | Area (2040) | €/kW (2040) |
|---|---|---|---|
| 7 | 300 | 7 | 250 |
| 6 | 320 | 6 | 267 |
| 5 | 350 | 5 | 292 |
| 4 | 380 | 4 | 317 |
| 3 | 420 | 3 | 350 |
| 2 | 460 | 2 | 383 |
| 1 | 500 | 1 | 417 |

Lifetime is set to 20 years in 2030 as according to [41] the average lifetime of a solar panel is around 20-25 years. For simplicity it is assumed for this research that the lifetime for a solar PV panel in 2040 is the same as for 2030 .

## THE CAPEX OF THE WIND TURBINE SYSTEM

Table 28 depicts the lifetime, and the capex of the wind turbine system in 2030 and 2040.

**Table 28 Input variables wind turbine in 2030 and 2040**

| Input | 2030 | 2040 |
|---|---|---|
| CAPEX [€/kW] | 1800-1200 | 1500-1000 |
| Lifetime [yr] | 20 | 20 |

The capex is determined the same way as the solar PV panel capex. The Capex is calculated by taking two checkpoints in areas between the intervals of 5-12 m/s. Then the capex is distributed dynamically between these two checkpoints to create a realistic view of the capex in 2030 and 2040, as cost vary between areas of high and low mean windspeeds. According to [38] [48] [40] the capex can be estimated to be between 1800-1200 €/kW in 2030 and 1500-1000 €/kW in 2040, depicted in table 29. The capex for 2040 is calculated the same way as for the solar PV panels.

**Table 29 Capex range for wind turbine in 2030 and 2040**

| Area (2030) | €/kW (2030) | Area (2040) | €/kW (2040) |
|---|---|---|---|
| 7 | 1200 | 7 | 1000 |
| 6 | 1300 | 6 | 1083 |
| 5 | 1400 | 5 | 1167 |
| 4 | 1500 | 4 | 1250 |
| 3 | 1600 | 3 | 1333 |
| 2 | 1700 | 2 | 1417 |
| 1 | 1800 | 1 | 1500 |

Lifetime is set to 20 years in 2030 as according to [49] the average lifetime of a wind turbine is around 15-25 years. It is assumed that the lifetime for a wind turbine in 2040 is the same as for 2030.

### THE LEVELIZED COST OF ELECTRICITY FOR THE SOLAR AND WIND COMBINATION

For the solar and wind combination the input variables are the intermediate results of the calculations for the yield and LCOE for solar and wind. This is shown in table 30. With the LCOE of the solar PV system and wind turbine system for 2030 and 2040 the average LCOE for the solar and wind combination can be determined.

**Table 30 Input variables solar and wind 2030 and 2040**

| Input | 2030 | 2040 |
|---|---|---|
| LCOE solar [€/kWh] | 0.014 - 0.052 | 0.010 – 0.039 |
| LCOE wind [€/kWh] | 0.02 – 0.088 | 0.017 – 0.066 |

### THE CAPEX FOR THE ELECTROLYZER

Table 31 depicts the lifetime, and capex of the electrolyzer system in 2030 and 2040.

**Table 31 Input variables electrolyzer in 2030 and 2040**

| Input | Value 2030 | Value 2040 |
|---|---|---|
| CAPEX [€/kW] | 250 | 150 |
| Lifetime [yr] | 10 | 15 |

The capex of the electrolyzer technology is a one-off cost that occurs during construction of the system before commissioning. [63] shows that low capex and electricity cost will be realized in ‘off-grid’ multi-GW solar and wind hydrogen powerplants at the most optimal locations. The capex cost range is given between 250-500 €/kW. Looking at figure 31 this correlates with a learning rate of technology of 12% for 2030. This research considers a capex of 250 €/kW for 2030. The capex for 2040 is determined by assuming the highest learning rate for 2030, 20%, as a base set for the price in 2040, shown in figure 57 [7]. [63] also indicates a price range below 200 €/kW between 2030 and 2050 for electrolyzer technology. 2040 electrolyzer price is set at 150 €/kW.

Lifetime of the electrolyzer is assumed to be 10 years in 2030 as the lifetime of today’s alkaline electrolyzer is already 7 years [32]. [26] implies that alkaline technology will have a lifetime of around 12 years in 2050 and [87] implies a lifetime of around 13 years in 2050. This research considers an optimistic view on electrolyzer lifetime in 2040 and assumes a lifetime of 15 years.

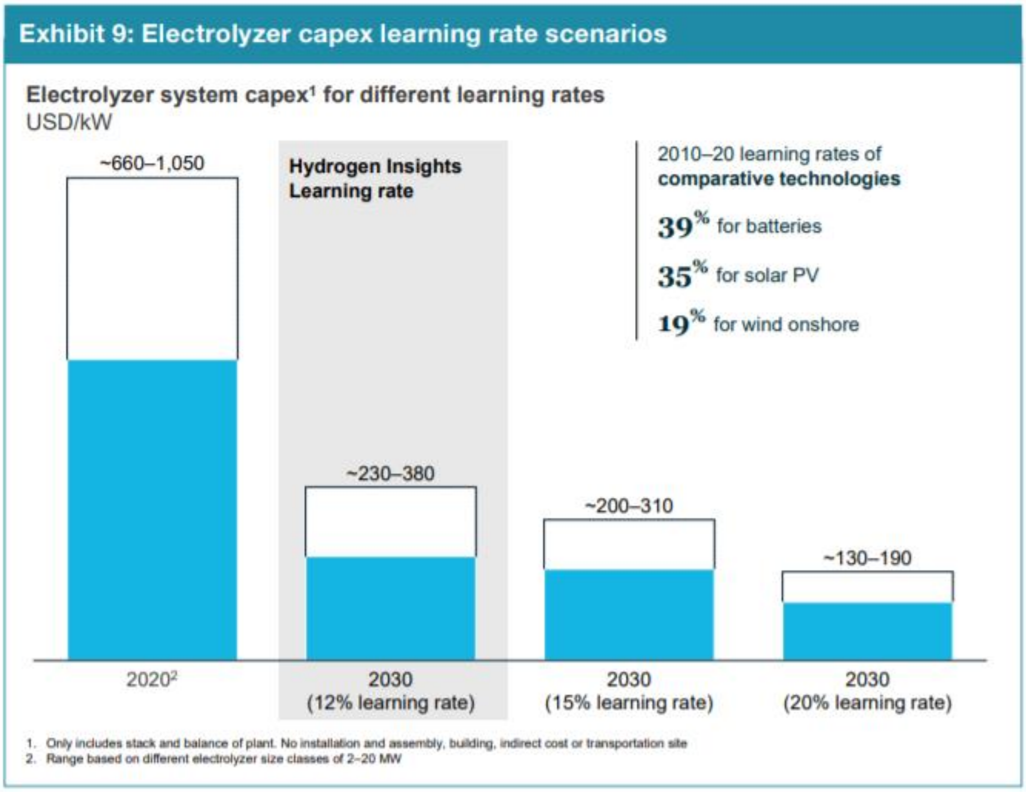


Figure 56 Electrolyzer capex learning rate scenarios for 2030 and other technologies e.g., batteries, solar, and offshore wind [7]

# 3 RESULTS

In this chapter the results of this research are shown. First, the results of the geospatial analysis with the 500km$^2$ and 1000km$^2$ size criterion for the solar, wind, and the solar and wind combination are shown. The LCOH of the 7 regions for solar, wind, and the solar and wind combination are implemented into the final suitability maps to depict the suitable and low-cost areas in Europe and North Africa. Afterwards, the area- and electrolyzer size needed per renewable energy source per area for a minimum production of 1 million tons is shown. In addition, the production price fluctuation due to transport and storage costs, and land prices is shown. Also, the difference in production potential by adjusting the size criterion is depicted.

## 3.1 SOLAR ENERGY TO HYDROGEN SCENARIO

The final suitability map for solar panel placement for areas larger than 500km$^2$ is shown in figure 57. The map indicates 7 different areas as classification for low and high solar power potential output. According to the analysis there is more space for solar panel placement outside the boundaries of Central-Europe e.g., Mediterranean region, South- and East-Europe.

It is seen in figure 57 that the areas suitable, and with enough space, are countries with low population density e.g., Western-Sahara and mostly situated in North Africa. Combining the LCOH shows that countries from Spain and Southwards are competitive for low-cost green hydrogen production in 2040.

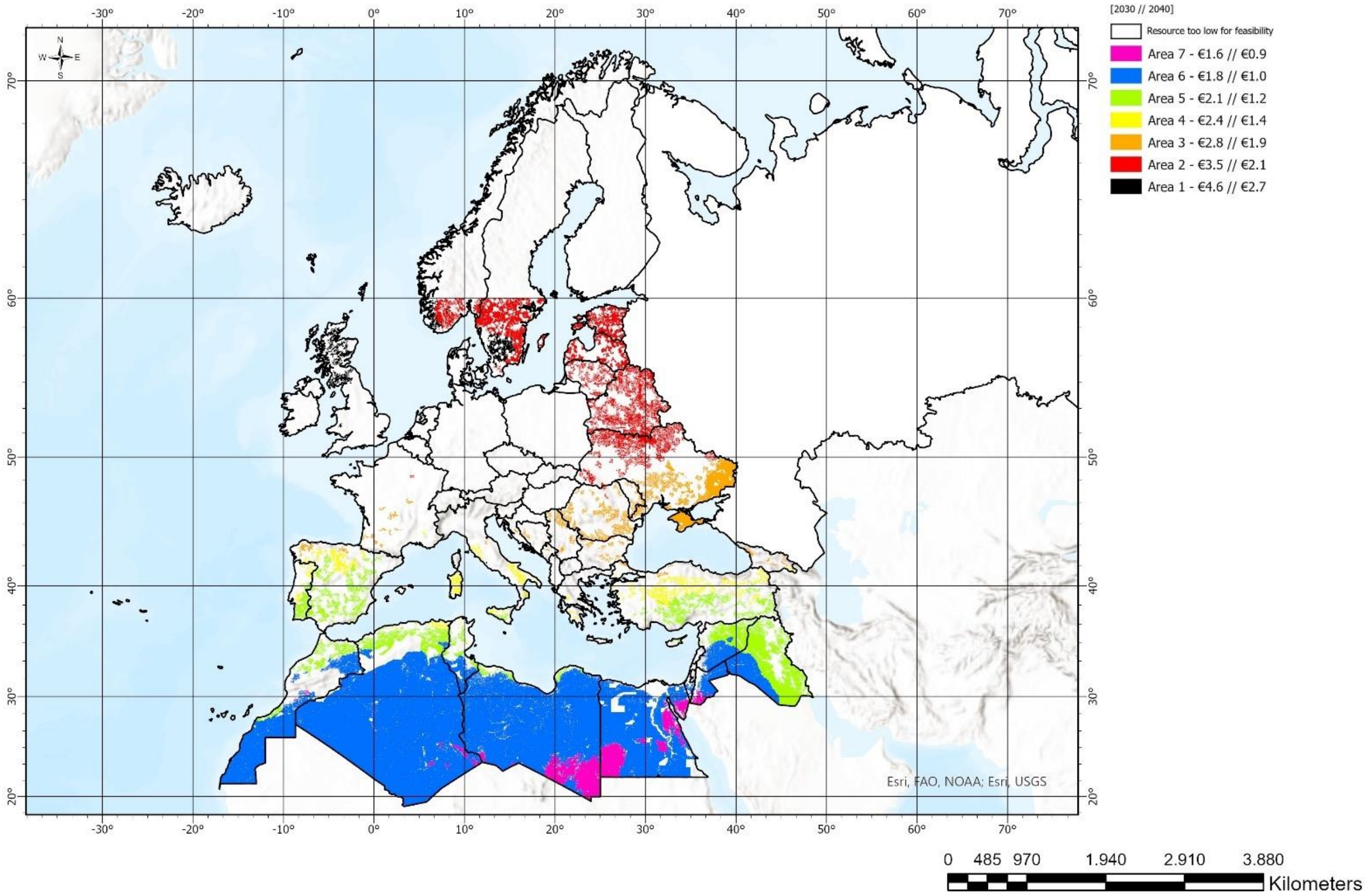


**Figure 57 Suitability map solar scenario areas >500km2. The most optimal and cheapest areas are located in North-Africa and South-Europe in 2040.**

Table 32 shows the LCOH for solar PV panels as a renewable energy source per area. Solar energy shows to be below 1.5 €/kg for the areas 4-7 in 2040. These areas have a solar output potential of 1400-2200 kWh/kWp. In 2030 there are no areas with a production price lower than 1.5 €/kg.

Table 32 LCOH of solar energy for green hydrogen production in 2030 and 2040. The majority of the areas are feasible in 2040.

| *AREA* | kWh/kWp | *2030* | *2040* |
|---|---|---|---|
| *7* | 2200-2000 | € 1.6 | € 0.9 |
| *6* | 2000-1800 | € 1.8 | € 1.0 |
| *5* | 1800-1600 | € 2.1 | € 1.2 |
| *4* | 1600-1400 | € 2.4 | € 1.4 |
| *3* | 1400-1200 | € 2.8 | € 1.9 |
| *2* | 1200-1000 | € 3.5 | € 2.1 |
| *1* | 800-1000 | € 4.6 | € 2.7 |

In table 33 the amount of million tons of hydrogen per 500km$^2$ per area and the area size needed for 1 million tons of hydrogen production in 2030 and 2040 is shown.

Table 33 Hydrogen production in Million tons per 500km2 and Area size for 1 million tons of hydrogen in 2030 & 2040.

|  | *2030* | *2040* | *2030* | *2040* |
|---|---|---|---|---|
| **Area** | **Mton H2 per 500 km2** | **Mton H2 per 500 km2** | **Area size for 1Mton of hydrogen (km$^2$)** | **Area size for 1Mton of hydrogen (km$^2$)** |
| 7 | 2.40 | 2.87 | 208 | 174 |
| 6 | 2.09 | 2.50 | 239 | 200 |
| 5 | 1.80 | 2.16 | 278 | 231 |
| 4 | 1.57 | 1.88 | 319 | 266 |
| 3 | 1.32 | 1.58 | 379 | 316 |
| 2 | 1.02 | 1.22 | 490 | 410 |
| 1 | 0.80 | 0.96 | 625 | 521 |

The results show that the areas with higher annual solar power output potential produce more hydrogen than in areas with lower potential due to higher solar irradiance. In addition, due to more efficient technology, the production per area also increases in 2040. The area size for solar panel placement differs between 208 - 625 km$^2$ for 2030 to produce 1 million tons of hydrogen. For 2040 is varies between 174 - 521 km$^2$. It is also seen that around 490 km$^2$ for 2030 and 410 km$^2$ is needed to produce 1 million tons of green hydrogen. For the most optimal areas the required space is below 500 km$^2$, which is reasonably small compared to the amount of space available in these regions e.g., North-Africa.

In table 34 the electrolyzer capacity to produce 1 million tons of hydrogen is shown. The results show that the amount of installed solar PV panels influences the electrolyzer capacity. The low rated power of the PV panel, when compared to the that of the wind turbines, means that this system has a large quantity of panels to produce 1 million tons. In the worst regions, area 1, the capacity is around 50 GW. In 2040, the capacities are smaller due to higher efficiencies.

**Table 34 Electrolyzer capacity (GW) per 1 million tons of hydrogen production in 2030 & 2040. The electrolyzer capacity is high for solar due to the amount of installed solar PV systems needed for the production for a minimum of 1 million tons of green hydrogen.**

| | *2030* | *2040* |
|---|---|---|
| **Area** | **Electrolyzer capacity 1Mton (GW)** | **Electrolyzer capacity 1Mton (GW)** |
| 7 | 23 | 22 |
| 6 | 26 | 2 |
| 5 | 28 | 2 |
| 4 | 32 | 30 |
| 3 | 36 | 34 |
| 2 | 43 | 40 |
| 1 | 53 | 50 |

Appendix B shows the hydrogen production potential in 2030 and 2040 for the solar scenario looking at areas larger than 500 km$^2$. The potential increases in 2040 due to the use of more advanced wind turbines with higher efficiencies. In addition, the last table shows the potential in 2040 for areas with a production price lower than 1.5 €/kg. It shows that the potential of Europe reduces due to the amount of less suitable areas located in that region that don’t make the aforementioned threshold.

## 3.2 WIND ENERGY TO HYDROGEN SCENARIO

The final suitability map for wind turbine placement for areas larger than 1000km$^2$ is shown in figure 59. The map indicates 7 different areas as classification of low and high windspeeds. According to the analysis there is more space for wind turbine placement outside the boundaries of Central-Europe e.g., Mediterranean region and part of Scandinavia.

The map seen in figure 58 shows that the areas suitable, and with enough space, are countries with low population density e.g., Western-Sahara, like the solar scenario. Certain areas with high mean windspeeds, e.g., Ireland and UK, are not shown in figure 58 because of the number of natural beauty areas located within these regions. When adding the LCOH of wind energy for green hydrogen production it is seen that countries around the North- and Baltic Sea, countries in North Africa, and some regions in Eastern Europe are suitable for low-cost production. Only Western-Sahara is competitive in 2030 for wind energy.

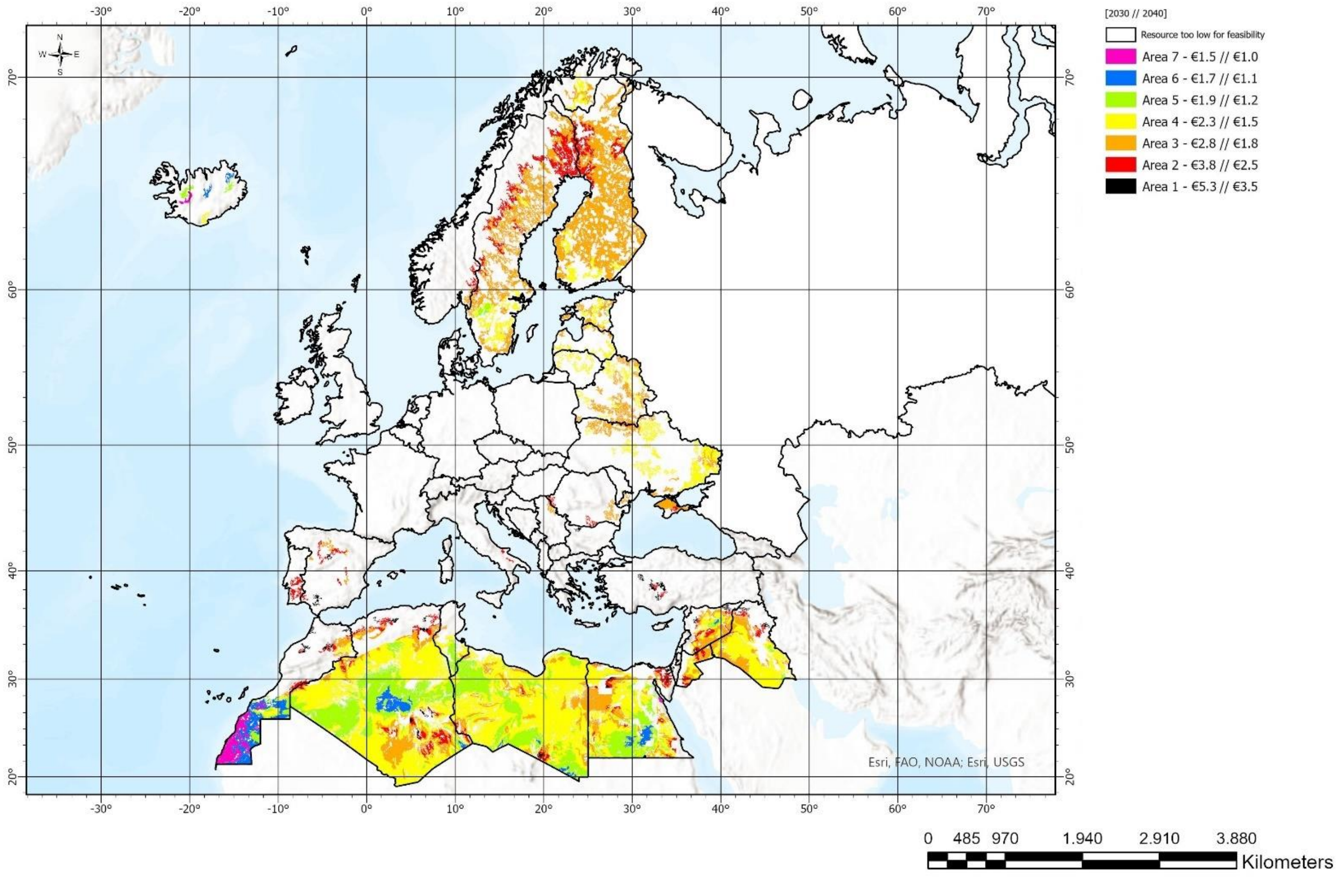


Figure 58 Suitability map wind scenario areas >1000km2. The most optimal and cheapest areas are located in Norway and North-Africa in 2040.

Table 35 shows that wind powered water electrolysis for green hydrogen production is already competitive in 2030 in the most optimal area, whereas in 2040 wind energy can be produced for the same, and lower, price of low carbon hydrogen production in areas 4-7, which are 8-12 m/s mean windspeed regions.

**Table 35 LCOH of wind energy for green hydrogen production in 2030 and 2040. In 2040 the majority of the areas are feasible for low-cost green hydrogen production (<1.5€/kg).**

| ***AREA*** | **m/s** | ***2030*** | ***2040*** |
|---|---|---|---|
| ***7*** | 11-12 | € 1.5 | € 1.0 |
| ***6*** | 10 | € 1.7 | € 1.1 |
| ***5*** | 9 | € 2.3 | € 1.2 |
| ***4*** | 8 | € 2.4 | € 1.5 |
| ***3*** | 7 | € 2.8 | € 1.8 |
| ***2*** | 6 | € 3.8 | € 2.5 |
| ***1*** | 5 | € 5.2 | € 3.5 |

In table 36 the amount of million tons of hydrogen per 1000km$^2$ per area and the area size needed for 1 million tons of hydrogen production in 2030 and 2040 for wind energy is shown.

**Table 36 Hydrogen production in Million tons per 500 km2 and Area size for 1 million tons of hydrogen in 2030 & 2040. The amount of space needed for 1 million tons of green hydrogen is larger than expected in 2030 and in 2040 only the most optimal area is suitable for the space criterion of 1000km$^2$.**

| | *2030* | *2040* | *2030* | *2040* |
|---|---|---|---|---|
| **Area** | **Mton H2 per 500 km2** | **Mton H2 per 500 km2** | **Area size for 1Mton of hydrogen (km$^2$)** | **Area size for 1Mton of hydrogen (km$^2$)** |
| 7 | 0.33 | 0.45 | 1515 | 1111 |
| 6 | 0.31 | 0.44 | 1613 | 1136 |
| 5 | 0.29 | 0.41 | 1724 | 1220 |
| 4 | 0.25 | 0.35 | 2000 | 1429 |
| 3 | 0.22 | 0.31 | 2272 | 1613 |

| | | | | |
|---|---|---|---|---|
| 2 | 0.17 | 0.24 | 2941 | 2083 |
| 1 | 0.13 | 0.15 | 3846 | 3333 |

When comparing to the solar scenario table 32 shows that the area size needed to produce 1 million tons of hydrogen is much larger. This is due to the spacing between wind turbines. The difference in size between the two wind turbines used, 6MW in 2030 and 10MW in 2040, affects the area size needed significantly. The most optimal areas only need 1111km$^2$ in 2040. The least feasible area in 2030 requires an area size of around 3846km$^2$ to produce 1 million tons of hydrogen. In addition, the actual area that a wind turbine needs for placement is small in comparison to the size determined for the total wind farm. The area needed per wind turbine is determined by the size of the base of the turbine. Economic activity such as agriculture can continue to happen between the placed wind turbines.

In table 37 the electrolyzer capacity per 1 million tons of hydrogen production is shown. The installed capacity is between 8 – 25 GW for 2030 and 2040, depending on the year and area.

**Table 37 Electrolyzer capacity (GW) per 1 million tons of hydrogen production in 2030 & 2040. The electrolyzer size is small in the most optimal areas in 2030 and 2040.**

| | *2030* | *2040* |
|---|---|---|
| **Area** | **Electrolyzer capacity 1Mton (GW)** | **Electrolyzer capacity 1Mton (GW)** |
| 7 | 9.4 | 8 |
| 6 | 9.8 | 8.4 |
| 5 | 10.6 | 9 |
| 4 | 12.3 | 10.5 |
| 3 | 14.1 | 12 |
| 2 | 18.5 | 15.8 |
| 1 | 24.6 | 24.6 |

Appendix C shows the hydrogen production potential in 2030 and 2040 for the wind scenario looking at areas larger than 1000 km$^2$. The potential increases in 2040 due to the use of more advanced wind turbines with a higher efficiency. Europe shows to have the least amount of potential when compared to North-Africa. In addition, Appendix C shows the potential of Europe and North Africa for areas below 1.5 €/kg. In both Europe and North Africa, the potential drops due to areas that are not seen as suitable by the 1.5 €/kg threshold.

## 3.3 SOLAR AND WIND COMBINATION ENERGY TO HYDROGEN SCENARIO

The final suitability map for the solar and wind scenario for areas larger than 500km$^2$ is shown in figure 59. The map indicates 7 different areas as classification of low and high solar power potential output and low and high mean windspeeds. According to the analysis there is more space for this hybrid system outside the boundaries of Central-Europe e.g., Mediterranean region, South- and East-Europe.

In addition, a combination of wind- and solar energy production provides more options for placement than solely relying on Solar or Wind as an electricity producer. Countries such as Spain, France, and Eastern-European countries show to be viable options for this scenario. The LCOH shows that almost all areas on the map are competitive with low-carbon hydrogen production in 2040. In 2030 only the Western-Sahara is competitive with low-carbon hydrogen production.

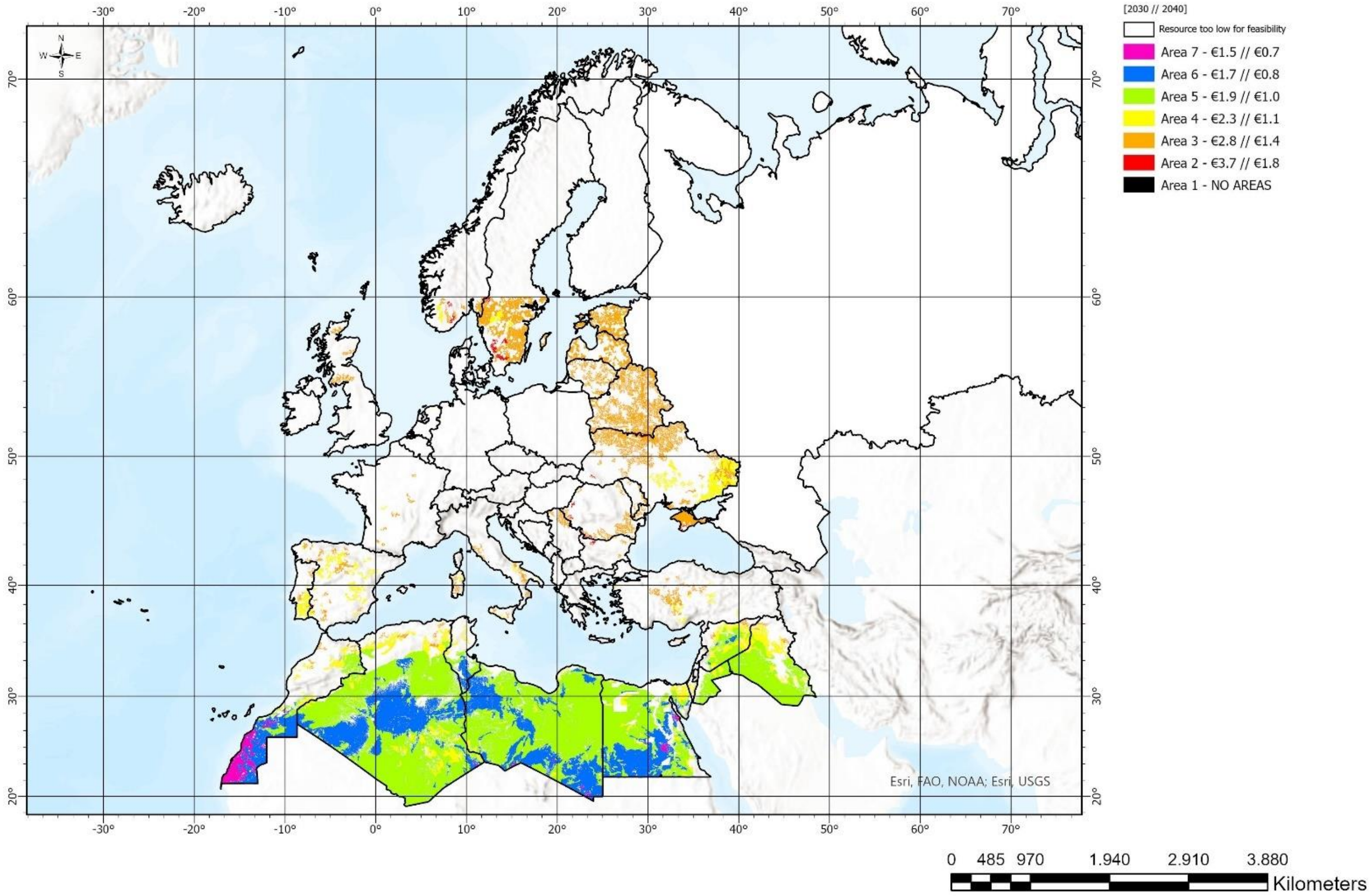


Figure 59 Suitability map Solar and Wind scenario areas >500km2. The most feasible locations are located in North-Africa.

Table 38 indicates that a combination of solar and wind energy is already competitive in 2030 for the most optimal regions and in 2040 it can produce green hydrogen lower than 1.5 €/kg from areas 2-7. These are regions with windspeeds between 7-12 m/s and solar power output potential between 1200-2200 kWh/kWp.

Table 38 LCOH of solar and wind energy combination for 2030 and 2040

| *AREA* | kWh/kWp | m/s | *2030* | *2040* |
|---|---|---|---|---|
| *7* | 2200-2000 | 11-12 | € 1.5 | € 0.7 |
| *6* | 2000-1800 | 10 | € 1.7 | € 0.8 |
| *5* | 1800-1600 | 9 | € 1.9 | € 1.0 |
| *4* | 1600-1400 | 8 | € 2.3 | € 1.1 |
| *3* | 1400-1200 | 7 | € 2.8 | € 1.4 |
| *2* | 1200-1000 | 6 | € 3.7 | € 1.8 |

The intermediate results of the load hours, electricity prices, hydrogen price per kilogram, electrolyzer capacity and amount of produced hydrogen per 500km$^2$ in 2030 and 2040 are shown in table 39 and 40. The electrolyzer capacity varies between 11 – 22 GW in 2030 and 2040, depending on the year and area. The amount of area needed for 1 million tons is between 204 – 373 km$^2$ in 2030 and between 167 – 307 km$^2$ in 2040.

Table 39 Load Hours, electricity price, hydrogen price, electrolyzer capacity (GW) and production amount per 500km2 Solar and Wind scenario 2030. The amount of area needed for 1 million tons of production with a solar and wind combination is between 204 – 373 km

| 2030 | | | | |
|---|---|---|---|---|
| **Area** | **Load hours** | **Electrolyzer capacity (GW)** | **Mton H2 per 500 km2** | **Area size for 1Mton of hydrogen (km$^2$)** |
| 7 | 4094 | 12.11 | 2.46 | 204 |
| 6 | 3759 | 13.19 | 2.16 | 221 |
| 5 | 3416 | 14.50 | 1.90 | 243 |
| 4 | 3038 | 16.29 | 1.64 | 273 |

| | | | | |
|---|---|---|---|---|
| 3 | 2678 | 18.50 | 1.37 | 310 |
| 2 | 2222 | 22.26 | 1.07 | 373 |
| 1 | *No areas feasible* | *No areas feasible* | *No areas feasible* | *No feasible areas* |

**Table 40 Load Hours, electricity price, hydrogen price, electrolyzer capacity (GW) and production amount per 500km2 Solar and Wind scenario 2040. The amount of area needed for 1 million tons of production with a solar and wind combination is between 204 – 373 km**

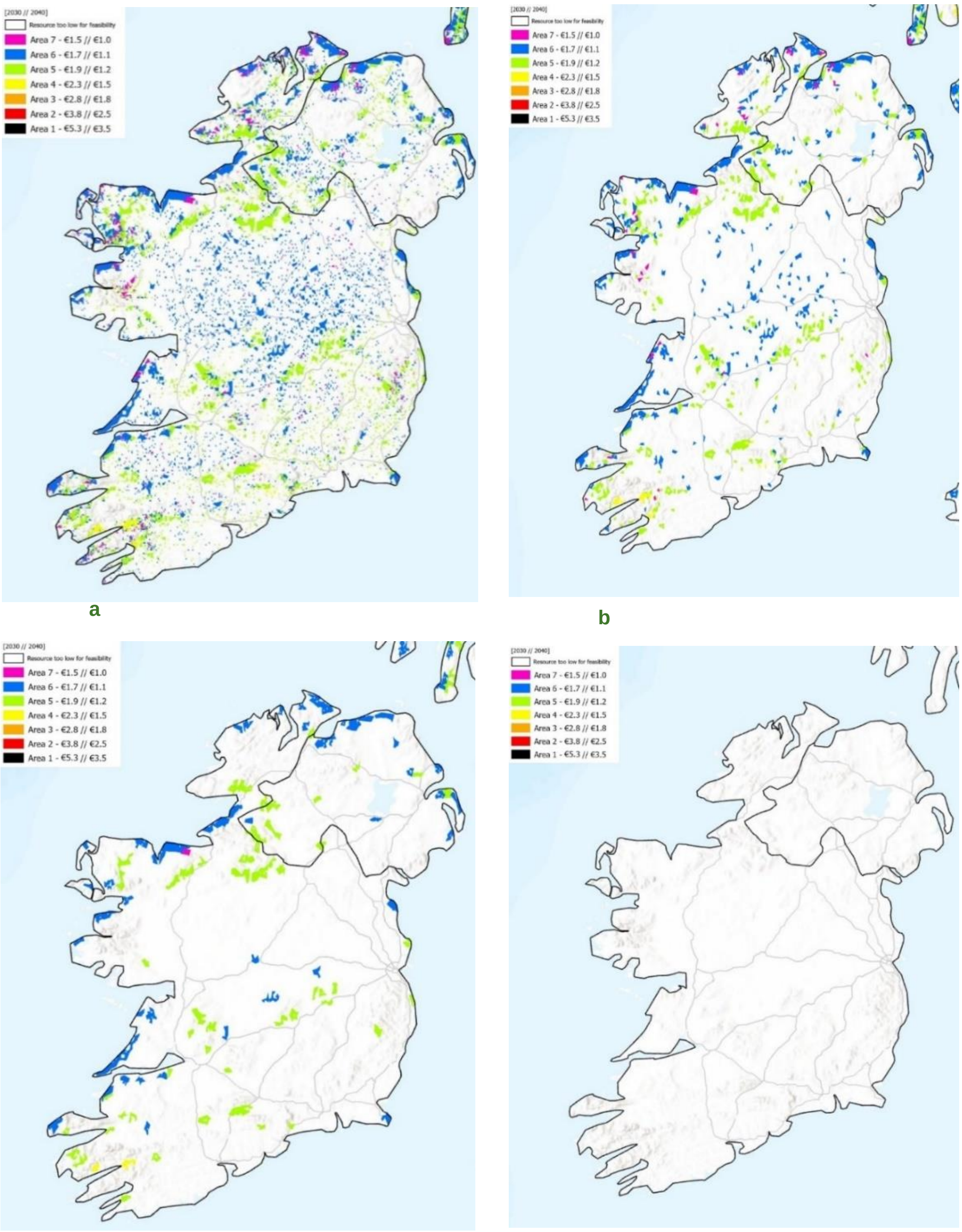
| 2040 | | | | |
|---|---|---|---|---|
| **Area** | **Load hours** | **Electrolyzer capacity (GW)** | **Mton H2 per 500 km2** | **Area size for 1Mton of hydrogen (km$^2$)** |
| 7 | 4162 | 11.20 | 3.01 | 167 |
| 6 | 3824 | 12.18 | 2.65 | 181 |
| 5 | 3477 | 13.39 | 2.33 | 199 |
| 4 | 3090 | 15.07 | 2.01 | 224 |
| 3 | 2723 | 17.09 | 1.69 | 254 |
| 2 | 2256 | 20.66 | 1.32 | 307 |
| 1 | *No areas feasible* | *No areas feasible* | *No areas feasible* | *No feasible areas* |

Appendix D show the hydrogen potential for the solar and wind hybrid system for areas larger than 500km$^2$. This combination of solar and wind shows large potential in North Africa but smaller potential in Europe. Also, unlike with the solar and wind scenario, the potential of the solar and wind combination drops by a small amount by 2040 while handling the 1.5 €/kg threshold.

## 3.4 SENSITIVITY

### 3.4.1. GIS SIZE CRITERION

The amount of potential per country varies when the size criterion in the models is adjusted. In this case, the wind scenario is selected to do an in-depth analysis to the effect of change in the size criterion to the real potential, shown in figure 60a-d. The change in production amount is depicted in table 41.



a b

c d

**Figure 60 (a-d) Size criterion change effect on available areas for wind turbine placement with hydrogen prices in [2030 // 2040]. a: 1km2, b: 5km2, c: 20km2, d:200km2 . The lower size criterion shows more potential in Ireland.**

The difference in production potential in km$^2$ due to change in the size criterion in 2040 for a hydrogen production price below €1.5/kg is shown in table 43 for the size criterion change in figure 60 a-d. As can be seen, the potential increases when lowering the size criterion from 200 – 1 km$^2$. This shows that the size criterion has a major influence on the geographical hydrogen potential in this research.

**Table 41 Effect of variation in size criteria on hydrogen production amount in 2040 – wind scenario. The lower the size criteria are the more potential is revealed in the area.**

| Area | Windspeeds (m/s) | €/kg (2040) | 200km$^2$ Size criterion | Mton H2 | 20km$^2$ Size criterion | Mton H2 | 5km$^2$ Size criterion | Mton H2 | 1km$^2$ Size criterion | Mton H2 |
|---|---|---|---|---|---|---|---|---|---|---|
| **7** | 11-12 | 1.0 | 86240 km$^2$ | 80 | 99091 km$^2$ | 92 | 110304 km$^2$ | 102 | 131863 km$^2$ | 123 |
| **6** | 10 | 1.1 | 203204 km$^2$ | 180 | 236062 km$^2$ | 209 | 258057 km$^2$ | 228 | 317209 km$^2$ | 281 |
| **5** | 9 | 1.2 | 1144832 km$^2$ | 945 | 1235648 km$^2$ | 1021 | 1293989 km$^2$ | 1069 | 1410517 km$^2$ | 1165 |
| **4** | 8 | 1.5 | 2747196 km$^2$ | 1945 | 2977584 km$^2$ | 2108 | 3098477 km$^2$ | 2193 | 3283305 km$^2$ | 2324 |

### 3.4.2. INCLUDING TRANSPORT & STORAGE COSTS TO THE LCOH

The final production price depends on the location, and also its costs of storage. The amount of hydrogen is mostly converted into baseload, 8000 hours, but this depends on the distance and the costs of storage per location [107]. The levelized costs of storage are estimated to be 0.1€/kg in baseload and transport costs are 0.1 €/kg/1000km in baseload. This affects the production price of hydrogen at the end. For example, to meet the hydrogen demand of Germany it can look at two options: (1) produce the hydrogen itself or (2) import it from another country where the total combined costs of production, including transport and storage, are lower than Germany's own production price. Taking the solar energy scenario as an example, considering a country with a high solar power output in Europe and North Africa, and looking at the production prices it can be determined whether Germany is more likely to import from other countries in 2030 and 2040. A region with the highest solar power output possible in Spain and North Africa and closest to North-West Germany is assumed, indicated with an orange star in figure 61. Also, an area with an intermediate high solar power output potential in South-France is looked at, as this region is close to Germany. North-West Germany is the most ideal location in Germany for salt cavern storage [16].

In addition, assuming the hydrogen pipeline system mentioned in chapter 1 the natural gas pipeline system in this figure is used as an example to indicate the effect distance on transport for the overall production price. From the North African region, it is around 3500km to the Ruhr area and from the region in Spain around 1600km. From South-France to the Ruhr area, it is around 800km. These regions have a production price below 1.5€/kg.

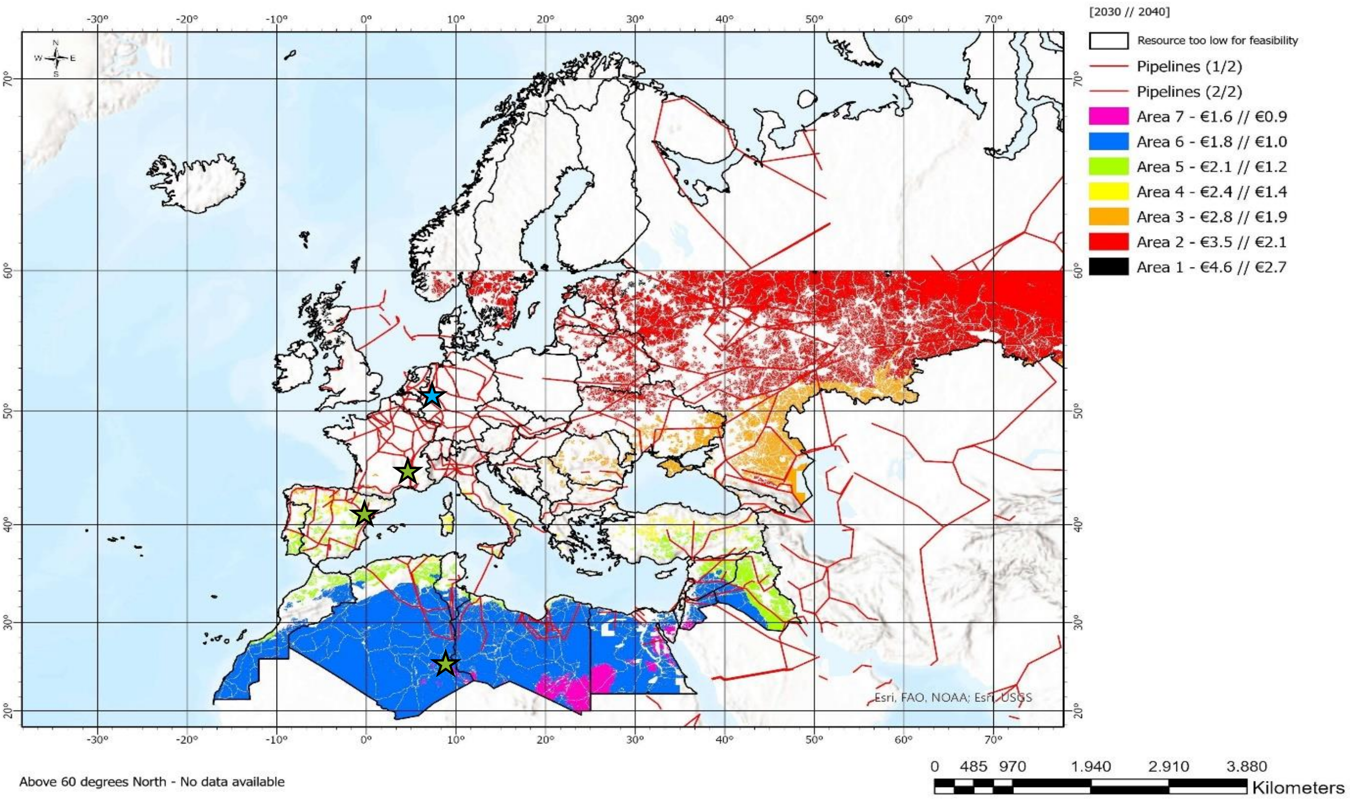


**Figure 61 Final suitability map solar scenario for 2030 and 2040 including natural gas pipeline system for hydrogen transport. The green stars indicate the selected regions to show the effect of distance between potential hydrogen supply and demand hubs, which are indicated with the blue star.**

In table 40 the added costs, in baseload, for the import of green hydrogen from Spain and North Africa are shown in 2040. In addition, the storage costs are assumed constant but in reality, these differ per country and per operation. 0.1 €/kg for salt cavern storage is on the lower range of values. The value is determined to be between 0.1 – 1.4 €/kg but differs on the operation [117]. It is assumed that the gains costs are closely related to the amount of hydrogen affected during underground storage (maximum quantities for storage, flow and rhythm of injections and withdrawals during the operating period of storage [118]. Thus, the size and quality of the salt cavern influences the price of storage. This has to be determined at the site of the operation itself and can’t be assumed per region for this research, thus the lower range of the values is taken as an estimate. For a pan-European import of hydrogen, Germany can import from Spain also in 2040, as the costs are low enough. When looking at the wind scenario in figure 62 the transport costs are heavily reduced in Europe as the distance from the most optimal regions to North-West Germany has decreased from the most optimal region with low hydrogen costs in Sweden.

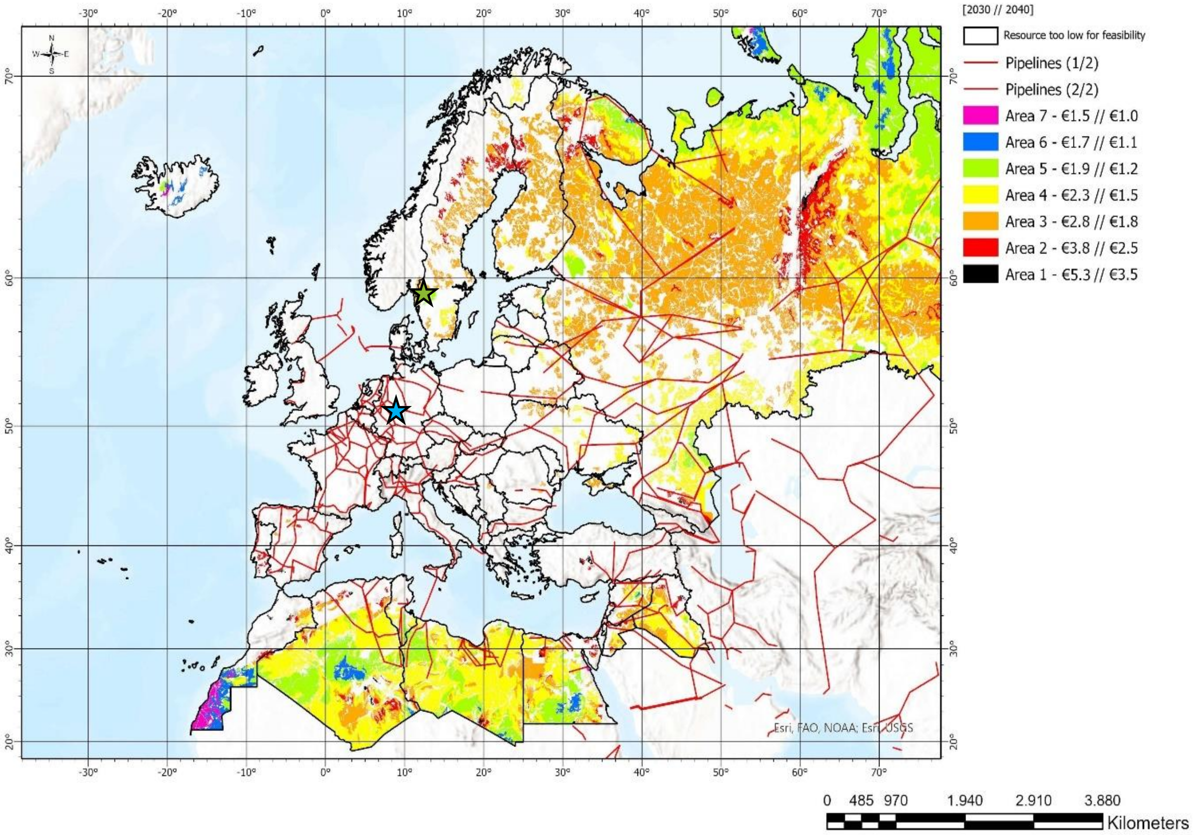


**Figure 62 Final suitability map wind scenario for 2030 and 2040 including the natural gas pipeline system for hydrogen transport. The same is done for the wind scenario as the solar scenario.**

Looking at table 42 it can be said that Spain and Norway are competitive for low-cost green hydrogen in 2040 in Europe. Also, it shows that for the solar scenario Germany is better off importing from North Africa against low prices even though the distance to North-West Germany is large but for the wind scenario the cheaper option is to import green hydrogen from Norway, which has a short distance to North-West Germany and a lower production price than Germany itself.

Table 42 Overall costs for green hydrogen production, including transport and storage, for 2040 from 3 different regions handling 3 different solar power output potential (yellow), 2 different regions handling 2 different mean windspeeds (Blue), and distance to North-West Germany

| Country | Distance to North-West Germany (km) | Transport costs (0.1€/kg/1000km) | Storage costs (0.1€/kg) | Production price most optimal region 2040(€/kg) | Overall production price 2040 (€/kg) |
|---|---|---|---|---|---|
| North-West Germany | 0 | 0 €/kg | 0 €/kg | 2.1 €/kg | 2.1 €/kg |
| South-Algeria | 3500 | 0.35 €/kg | 0.1 €/kg | 0.9 €/kg | 1.35 €/kg |
| North-Spain | 1600 | 0.16 €/kg | 0.1 €/kg | 1.2 €/kg | 1.46 €/kg |
| South-France | 800 | 0.08 €/kg | 0.1 €/kg | 1.4 €/kg | 1.58 €/kg |
| North-West Germany | 0 | 0 €/kg | 0 €/kg | 1.5 €/kg | 1.5 €/kg |
| Norway | 500 | 0.05 €/kg | 0.1 €/kg | 1.2 €/kg | 1.35 €/kg |
| South-Algeria | 3700 | 0.37 €/kg | 0.1 €/kg | 1.1 €/kg | 1.57 €/kg |

### 3.4.3. HYDROGEN PRODUCTION POTENTIAL

The potential is determined by the amount of space available, renewable energy resource. The dataset for the area size of the countries has to be checked first in order to make sure that the land sizes are in line with the real land size. In appendix F the sensitivity analysis is shown to what extent the areas of the countries in the model are the true areas used during modelling. The analysis shows that the real area sizes of the countries differ 93.92% from the area sizes used in the models. This indicates that the total production is 6.08% lower than calculated. This is shown in table 43.

**Table 43 Amount of hydrogen produced accumulating for real size of land in 2040. Due to the difference in the size of the countries used in the datasets and the real size of a country the total amount of hydrogen produced decrease.**

| **Scenario** | **Mton H2** | **Sensitivity analysis** | **Real H2 amount (Mton)** |
|---|---|---|---|
| Solar | 27196 | - 6.08% | 25542 |
| Wind | 1100 | - 6.08% | 1033 |
| Solar and Wind | 26751 | - 6.08% | 25125 |

The amount of potential is different in reality due to the difference in land size from the datasets. The land size is 1% smaller in the datasets than in reality, which indicates that more potential can be found in the suitable areas.

# 4 DISUCSSION

In this chapter, the relations, complexities, assumptions, limitations, and other considerations will be addressed. Firstly, the methodology is assessed to see whether a geospatial research is a solid method to determine the LCOH and production potential in Europe and North Africa. Then the ArcGIS Pro, LCOH and potential models are assessed whereas the results are compared to literature and discussed.

## 4.1 METHODOLOGY

In chapter 2 it is already mentioned that a geospatial techno-economic analysis has a valuable contribution to obtaining the suitable areas based on criteria. The techno-economic part focusses on the areas gained from the geospatial section and shows the feasibility based on economic and technical parameters used in this suitability study. This method enabled visual mapping of location performance with pre-selected datasets in this research. This provided insights on the regions in Europe and North Africa on where to produce green hydrogen at low-cost. Also, it provided aid on determining the effect of time in the model by considering different technical aspects of the technology used in 2030 and 2040. This made it easier to explore patterns in the research e.g., lower solar prices in locations with high solar power output potential and link available area size to production amount per region. In retrospect, the geospatial assessment used is similar to the ones used in multiple studies done on determining the LCOH and production potential [4][5]. It shows that the geospatial assessment is a solid method for this research.

For the cost model it is important to mention that the methodology from [78] and [80] is adopted partially and altered were deemed necessary. This thesis considers input values based on present forecasting of costs and technical parameters for the technology used in this research e.g., solar PV, wind turbines and electrolysers. A certain number of factors e.g., water desalination and labor costs are left out of this equation for simplicity but adding them to the overall price calculations will enhance the accuracy of the overall production price. However, this is determined by the scale and main purpose of the research.

The most important thing to realize is that for all renewable energy resource scenarios the credibility of the results is dependent on the datasets and parameters used in this research. Estimating the future economic and technical values have a large impact on the overall production price of hydrogen. This research estimated the input values for the overall production price in 2030 and 2040 by looking at hydrogen studies from e.g., McKinsey, IEA, Bloomberg. Some costs were left out e.g., sea water transport in the desert but these costs are seen as negligible in this research. Using parameters more in line with other research papers of hydrogen road maps may give results similar to the more generally forecasted production prices.

## 4.2 GEOGRAPHICAL HYDROGEN POTENTIAL

The GIS program allows for an accurate depiction of the suitability in the chosen regions. However, using this program comes with its difficulties as it hasn't improved certain bugs in its software. This makes it difficult to model large datasets. The overarching problems in using GIS for this research is rooted in three main reasons. The first is the availability of datasets, the second is the actuality of datasets, and the third is the precision of datasets. Correct and up-to-date datasets are hard to come by. The number of open-source datasets is limited and for certain datasets hefty fees are asked by companies and research institutions. This research uses population density data from 2016 and only a large portion of the European and North African cities are considered due to lack of data. However, this research provides a general overview of the potential for green hydrogen and not a specific answer on the matter.

The estimates of the renewable energy resources differ from other studies because of the differences in amount of input data for resource- and restricted areas [92][93][94]. For this research only the renewable energy potential, slope, and population density are considered to locate the suitable areas. To acquire more details in the results, the input datasets of the temperature, aspect slope, altitude, distance to electrical grid and land-use should be considered [75][77]. Restricted areas include cities, airports, and areas of natural beauty. However, roads, land-use and land cover are important factors to consider for exclusion areas [75][93]. But again, due to the large scale of this research, the addition of more datasets will not enhance the results as this research is to give a general overview of the overall potential in Europe and North Africa.

When narrowing the spatial analysis to certain smaller areas, the recommended datasets will become of more importance to the level of accuracy of the site suitability analysis.

The resolution of the datasets also determines the accuracy of the final suitability maps. The resolution is now set at around 1km$^2$, which for the scale of this research, is accurate enough. However, when doing the spatial analysis on a smaller scale, regional size for instance, the resolution must be smaller to maintain high accuracy in the model.

The ranking of the solar power output and mean windspeed data is set between 1-7, and most research uses a ranking system between 1-5 [21][24][94]. This gives a more precise depiction of renewable resources in the suitability model. This also enables to give a more price distinction over Europe and North Africa. Adding more classes to the ranking system increases

The buffer distance considered is estimated and likely exaggerated, as the average distance is between 2-5 km [23]. This indicates that even more potential can be found when adjusting the buffer size around the airports.

However, it must be said that due to the size criterion the amount of suitable space shown on the final maps is not realistic and more available space is to be found in these areas when reducing the size criterion, as mentioned in the results. In addition, the potential of the solar and wind combination is the highest between the three scenarios. This research considers that the solar panels are placed directly next to the wind turbines, which optimizes the available space. However, this is normally not the case when looking at similar projects [110]. Most solar and wind hybrid farms have a certain spacing between arrays of solar panels, which can reduce the amount of potential per area. The potential of the wind energy scenario is the lowest of the three scenarios due to the amount of spacing needed between the wind turbines.

## 4.3 TECHNICAL HYDROGEN POTENTIAL

The electrolyzer used in this research is an alkaline electrolyzer. It shows high efficiencies, long lifetime, and good upscaling possibilities. However, the choice of electrolyzer may differ in the future due to higher efficiencies and/or lower costs with other technologies. A more accurate assumption on the technological and economical input variables for the chosen electrolyzer can be made when it is known how this piece of equipment will develop in the near future.

For the solar and wind combination, the system is oversized by a ratio of 2. This represents the availability of the electrolyzer accommodating to the resource availability. In other words, solar and wind energy can be present at the same time during the day and the electrolyzer needs to be oversized to handle the load. The downside of oversizing is that the electrolyzer needs to be curtailed, which in turn reduces the capital efficiency of the solar and wind hybrid farm due to spilling of the renewable energy [119]. A ratio of 2 is considered due to the sheer size of the project, but the best ratio is found to be around 1.5.

In addition, it must be noted that the assumptions for the input variables of the total yield can have an influence on the validity of the calculations. Rotor diameter, rated power, lifetime of technology, solar panel size, spacing, and ground coverage ratio are all assumptions based on today’s knowledge. It is possible that these factors may vary in the future, giving a higher of lower hydrogen production price, which in turn can be estimated more correctly in the future.

## 4.4 ECONOMIC HYDROGEN POTENTIAL

In this research the suitable areas are considered as areas with a production price below 1.5 €/kg. The results show different areas for suitable locations, which depends on the renewable energy source used. For solar energy, the locations area found in South-Europe and North Africa in 2040. For wind energy, in 2030 the suitable areas are located in the Western Sahara and Iceland. In 2040, the potential is located in North-Africa, Eastern- and North Europe. For the solar and wind combination, suitable locations are found in the Western-Sahara in 2030 and all areas except Central Europe. Looking at figure 12 in chapter 1, it shows that this result agrees with the literature, but only for the solar and wind combination. When looking at figure 8 and 9 in chapter 1, the results of the solar scenario and wind scenario are also in agreement with the literature.

Looking at the results of the levelized costs of hydrogen for the three renewable energy scenarios it can be said that all scenarios show a competitive production price in 2040 for the majority of areas. This indicates that the production of green hydrogen can be competitive to grey hydrogen, with a carbon tax of €50, in the future. These results are in line with production prices of hydrogen estimated in [2][106].

The electricity prices in this research are calculated to be lower than the fossil fuel price range shown in figure 2. The electricity prices are dependent on the region, as in a region with more sun the solar electricity is cheaper to produce. As mentioned before, electricity prices are a key driver for hydrogen price reduction.

The capex for the solar, wind, and electrolyzer technology differ per area and are retrieved from governmental reports from a country in the lowest ranking (1) and from the highest ranking (7). From there the capex is estimated dynamically for the other areas (2-6). This gives a substantial result, as the results of the electricity prices are in line with what is estimated in literature. However, for a more precise depiction of the electricity price, more data on capex per country is needed.

When adding the transport and storage costs to the production price, it can be seen that the overall price increases. For Germany it is shown that importing hydrogen from wind energy from Norway is the cheapest option when comparing it to its own production price or importing it from North Africa. This indicates that storage and transport factors can determine the feasibility of hydrogen production per area at the end. The implication is that the feasibility differs by location of supply and demand.

The WACC averaged for this research and set to a fixed state for both 2030 and 2040. But in reality, the renewable energy systems are sensitive to changes in WACC, and this factor differs per country and per year [86]. However, for the scale of this research this is found to be sufficient enough to give reliable LCOH results.

## 4.5 GIS SIZE CRITERION

Appendix B, C and D show the total potential per country per area with the calculated price ranges. There is little known in literature on the potential of hydrogen per country, as GIS models are mostly used for small-scale research.

The results show that the production potential of Europe is around 1059 Mton for solar, 22 Mton for wind, and 2815 Mton for the solar and wind combination in 2040. For North Africa the production potential is estimated at 26181 Mton for solar, 2704 Mton for wind, and 24006 Mton for the solar and wind combination in 2040. Literature [62] suggest that hydrogen will make up for 24% of Europe's energy demand in 2050. This amounts to around 60 Mton of hydrogen needed. In the fourth tables in Appendix B,C and D show the energy consumption per country with a production price lower than 1.5 €/kg and their production potential. It indicates that there is enough hydrogen that can be produced and transported to meet the energy needs of North Africa and Europe combined. However, this means that the electrolyzer technology must make large improvements on up-scaling to even reach this goal.

The smaller the size criterion gets; the more potential is shown on the final suitability map. Effectively, it is shown that using the size criterion in a proper manner while modelling is extremely detrimental to the domestic energy import system of a country. The space criterion for this model is set to 1000km$^2$ for the wind scenario. But when lowering this criterion to 200-, 20-,5- and 1km$^2$ the available area on the maps increase as the weight of the restricted areas is then lowered by this criterion. This is done for Ireland as an example and the results are shown in figure 60a-d. Changing the criteria from 200 km$^2$ to 5 km$^2$ shows an increase of 22 Mton in production in Ireland. For this research, the smallest size criteria are set to be 5 km$^2$ for what is possible to place wind turbines or solar PV panels for green hydrogen production. Any size smaller than this is assumed to be used for electricity generation to the grid. It can be said that predetermining the size criterion for the size of the research is a must to get a high accuracy on the production potential.

Also, the size criteria considered for this research seems to be too high for the solar scenario and too low for the wind scenario. The solar and wind combination is left out for simplicity reasons. The difference in available area needed for solar PV panels to produce a minimum of 1 million tons of green hydrogen indicates that the geospatial model is able to show even more potential. For the wind scenario more space is needed to accomplish the 1 million tons minimum in 2030 and 2040. Only in 2040 for the most feasible area is an area size of 1000 km$^2$ required. There is little know in the literature on this matter and the only comparison are other future large-scale projects, which are mostly a combination of solar and wind hybrid systems.

# 5 CONCLUSION

The aim of this research is to determine the potential of large scale low-cost green hydrogen production in Europe and North-Africa. This in turn investigates the potential impact of implementing green hydrogen in the growing share of renewable energy on Europe's energy system. Europe's energy system is now made up of 18% renewables and the rest is made up of carbon-based energy products. Implementing green hydrogen to decarbonize this system can be a viable option for the future. A literature study is done in order to define the status quo regarding large scale green hydrogen systems as well as technological- and cost developments in technology for 2030 and 2040 that is required to set up such a system. With a geospatial techno-economic analysis the production price and production amount of green hydrogen is determined for 2030 and 2040. This research conducted this analysis for three scenarios of renewable energy: solar energy, wind energy and a combination of solar and wind energy. The research handles three main criteria for a suitable location for large scale green hydrogen production: Good solar and wind resources, low population density and a minimum available area of 500km$^2$ for solar and solar & wind, and 1000km$^2$ for wind. These size criteria are pre-estimated to be large enough to produce a minimum of 1 million tons of green hydrogen. For these areas to be considered competitive to low-carbon hydrogen, with a carbon-tax of 0.5 €/kg, in this research the production price must be below 1.5 €/kg.

A geospatial model is created in ArcGIS Pro that includes the solar power output potential and/or mean windspeeds, slope, and population density for the suitable areas. Furthermore, restricted areas are considered that include cities, airports, and areas of natural beauty. With the size criterion per renewable energy scenario the amount of available area is determined.

A cost model is then proposed, which includes the capex, opex, lifetime, efficiency, and technology characteristics of solar PV panels, wind turbines, and alkaline electrolysers for 2030 and 2040. Hydrogen storage and transport in the form of salt caverns and pipelines are included into the cost model to determine the overall hydrogen production price. Baseload is considered as standard for transport and storage of hydrogen depending on the location of supply and demand.

Then, a production potential model is considered to determine the amount of green hydrogen that can be produced in the suitable areas found in the geospatial model. Furthermore, the electrolyzer has been sized to match the power output of the wind turbines and solar PV panels for the solar and wind scenario. However, for the solar and wind combination a curtailment of 10% and an oversizing ratio of 2 are considered for the electrolyzer. The following conclusions can be made to answer the sub-questions, which in turn help to answer the main research question.

### *Sub-Question: Where are suitable locations and how much space is available in Europe and the North African region for large-scale green hydrogen production?*

A conclusion can be made by saying that Central Europe has little potential for solar and wind energy. The majority of the potential differs per renewable energy resources. For wind energy the potential is located in North-, and South Europe and in North Africa. For solar energy South Europe and North Africa are the most feasible locations. A combination of solar and wind energy shows more potential spread over Europe as the wind turbines and solar PV panels give a higher combined output than solely wind of solar energy. The only factor that is more beneficial for large scale production in North Africa is the amount of available space in comparison to Europe. In addition, the amount of area needed for the solar PV, and solar PV and wind turbine combination is less than the initial 500km$^2$ surface area for 1 million tons of green hydrogen production. This indicates that the size criterion in the GIS model can be lowered, which in turn increases the number of suitable areas. For the wind turbine system, the 1000km$^2$ space requirement is only met in the most optimal area in 2040. In addition, the results for the electrolyzer size are an indication on what scale these projects must be in the future per region in order to produce 1 million tons of green hydrogen. The results of the electrolyzer size are in line with other large scale green hydrogen projects.

### *Sub-Question: How can ArcGIS pro be adapted, handle input data and be validated for these hydrogen cost and potential calculations?*

Policy makers and economic developers need decision-making tools to help them conduct analysis, disseminate, and display results and make decisions on where to start and grow new businesses. ArcGIS Pro has proven to be a powerful tool in effectively delivering these functionalities and can be used by policymakers for visualization, modeling, analysis, and collaboration of renewable energy projects. The program helped obtain results that are in line with different research and governmental hydrogen roadmaps. This indicates that this program can be adapted to handle, by using the Model Builder, the input data to obtain the hydrogen cost and production potential. The validation is determined by the comparison of the results with other research, and in this case the results can be evaluated to be realistic.

### *Sub-Question: What is the levelized cost of hydrogen in 2030 & 2040 throughout Europe and the Mediterranean region as a function of the solar and wind resource?*

The results show that for the solar scenario the LCOH ranges between 1.6 - 4.6 €/kg in 2030 and 0.9 - 2.7 €/kg in 2040. For wind the LCOH ranges between 1.5 – 5.3 €/kg in 2030 and 1 – 3.5 €/kg in 2040. The solar and wind combination shows the lowest price range in 2030 and 2040 of 1.5 – 3.7 €/kg and 0.7 – 1.8 €/kg. It can be concluded that for the majority of the areas in 2040 for all three scenarios the production price of green hydrogen is lower than 1.5 €/kg. This indicates that producing green hydrogen in many regions a cheaper option is than producing grey hydrogen with a carbon tax of 0.5 €/kg. Including the transport and storage costs will increase the overall production price but these factors are location dependent. Countries such as Germany are better of importing from neighboring countries such as Norway due to the close proximity and good storage possibilities e.g., salt caverns. This lowers the costs made for these two factors. In addition, land prices can be a detrimental factor for the overall price, but this varies per country.

A conclusion can be made that the key drivers for these prices include the improvements of electrolyzer prices and efficiency, and the reduction renewable energy prices. The latter is region specific and depends on the accessibility to renewable energy resources (wind and sun). In reality, a more detailed financial overview of the solar costs per country and area must be made to determine the real prices.

***Sub-Question: What is the hydrogen production potential for large-scale low-cost (<1.5 €/kg) green hydrogen in Europe and the North African region in 2030 & 2040?***

It can be concluded that a large amount of green hydrogen can be produced in Europe and North Africa according to this research, but this depends on the renewable energy scenario. In 2040 the solar and wind combination produces the highest amount of green hydrogen in Europe, around 2815 Mton. For North Africa the solar scenario produces the highest amount of green hydrogen in 2040, around 26181 Mton. When considering that 24% of Europe's energy demand is estimated to be met by green hydrogen in 2040, it can be said that there is enough production potential in Europe alone to supply its own energy demand. Appendix B,C, and D show the potential in Europe and North Africa for the three renewable energy scenarios for 2030 and 2040 for all countries and for countries below 1.5 €/kg production costs. In table 44 the total production potential of Appendix B,C, and D per region, and scenario for 2030 and 2040 is shown. For the North Europe region, the countries of North and Central Europe are combined. It can be seen that there is enough potential for the solar, and solar and wind combination scenario in 2040 for cheap green hydrogen in Europe and North Africa. South European countries can possibly transport green hydrogen to Northern European countries if production prices allow it.

**Table 44 Hydrogen potential in North-Europe, South-Europe, and North Africa for the three different renewable energy scenarios in 2030 and 2040**

| **Region** | **Scenario** | **Potential 2030 (Mton)** | **Potential 2040 (Mton)** |
|---|---|---|---|
| North-Europe | Solar | 0 | 0 |
| South-Europe | Solar | 0 | 1059 |
| North Africa | Solar | 0 | 26181 |
| North-Europe | Wind | 1 | 22 |
| South-Europe | Wind | 0 | 0 |
| North Africa | Wind | 58 | 2704 |
| North-Europe | Solar and wind | 0 | 1483 |
| South-Europe | Solar and wind | 0 | 1332 |
| North Africa | Solar and wind | 493 | 24006 |

With the conclusions drawn from the sub-questions the main research question can be answered.

## ***“ What is the potential for low-cost large-scale green hydrogen production in Europe and the Mediterranean region in 2030 & 2040?”***

In vivo, the potential of low-cost green hydrogen production in Europe and North Africa is estimated to be large in the future. One would think that importing cheap green hydrogen from North Africa will be the best answer, but this research reveals that Europe can be a strong competitor and contributor of green hydrogen in 2040. This research shows Europe has to continue to import green hydrogen from North Africa, but the dependency decreases in 2040 as Europe is then more self-sufficient due to low green hydrogen production prices.

Looking at the case if green hydrogen has the capacity to develop into a solution in the future for decarbonizing the European energy system is dependent on three factors. The first is the space and resource availability in Europe and North Africa, which according to this research is abundant in North Africa and less abundant in Europe. For Europe more factors have to be considered into the geospatial analysis to accurately determine the amount of available space due to high population density and areas of natural beauty. In Europe wind energy thrives in the North and solar energy thrives in the South. For wind energy a larger amount of space is needed for the production of 1 million tons and for solar less. However, solar PV panels realistically take up more space as in between wind turbines the land is not covered and can be used for other purposes such as farming. A solar and wind hybrid system shows to be the most ideal option in Europe as it can be placed in more areas than the other two systems.

The second is the production price, which determines whether the area is competitive with grey hydrogen production with a carbon tax of 0.5 €/kg. In North Africa the production prices are the lowest in 2030 and importing from North Africa in 2030 shows to be the most feasible option. However, in some areas in North Europe e.g., Norway the production price is low enough to start producing cheap green hydrogen. In 2040, a majority of the areas in Europe are able to produce against low costs, which allows Europe to start supplying their own energy demands. In addition, it is shown that in 2030 there are already locations in Europe that can provide cheap green hydrogen by wind energy and a combination of solar and wind energy e.g., The North Sea area. This region is located close to hydrogen demand hubs e.g., The Netherlands and Germany, which makes it an attractive option for pan-European import. This makes green hydrogen more accessible in Europe as the production price can be as low as that in North Africa but with lower transmission costs. Transport and storage costs for baseload hydrogen adds around 0.1 €/kg per 1000km for transport and 0.1 €/kg for salt cavern storage.

The third is the production potential, which is the highest in North Africa and the lowest in Europe by a factor 10 for solar energy and the solar and wind hybrid system. The abundance of green hydrogen production potential in North Africa indicates that there is enough green hydrogen to decarbonize the energy system of Europe even more.

In table 45 an overview of the costs for production, transport per distance, and storage are depicted to show which regions are able to export green hydrogen and to what distance the hydrogen can be transported and still be competitive. In addition, the table shows at what price a region must import green hydrogen. This is when production prices are equal to 1.5 €/kg, because adding transport- and storage costs will make the hydrogen not competitive anymore with low carbon produced hydrogen. Green hydrogen produced at 1.4 €/kg is competitive and adding storage costs will give an overall price of 1.5 €/kg. However, for this price it becomes difficult to transport the hydrogen because of the price then becoming too high and not staying competitive. For these regions the produced hydrogen is better used for own national energy demand until the production price starts to decrease in the future. For production prices from 1.3 to ≤ 1.0 €/kg transport is possible but is determined by the maximum allowable distance, including storage, in order to keep the green hydrogen competitive.

**Table 45 Determination of whether a country should import, export, or self-produce and use the locally produced green hydrogen for its own national energy demand**

| Production price (€/kg) | Max. distance for transport (km) | Transport costs (€/kg) | Storage costs (€/kg) | Overall costs (€/kg) | This region must import or export or self-produce |
|---|---|---|---|---|---|
| 1.5 ≥ | NA | NA | 0.1 | 1.6 ≥ | Import |
| 1.4 | 0 | 0 | 0.1 | 1.5 | Self-produce with no export |
| 1.3 | 1000 | 0.1 | 0.1 | 1.5 | Export with max distance 1000 km |
| 1.2 | 2000 | 0.2 | 0.1 | 1.5 | Export with max distance 2000 km |
| 1.1 | 3000 | 0.3 | 0.1 | 1.5 | Export with max distance 3000 km |
| 1.0 | 4000 | 0.4 | 0.1 | 1.5 | Export with max distance 4000 km |
| < 1.0 | 5000 ≥ | 0.5 ≥ | 0.1 | 1.5 | Export with max distance ≥ 5000 km |

Combining the results for the levelized costs of hydrogen and the addition transport & storage costs, shown in table 45, while considering the final potential of Europe and North Africa, the following maps can be concluded for the import and export of green hydrogen in Europe and North Africa in 2040. The European countries colored yellow must import green hydrogen from the countries colored blue. This is due to the lack of resources in the yellow regions. Green regions must export green hydrogen to orange regions due to lack of potential in the orange regions. The green regions are able to produce green hydrogen at low enough prices that transport and storage costs don’t affect the overall production price when exported to the orange regions. The potential production areas in Italy are located in the southern region, which makes the distance from there to the yellow regions still too large. Table 46 shows the green hydrogen import/export system of all countries for solar in 2040.

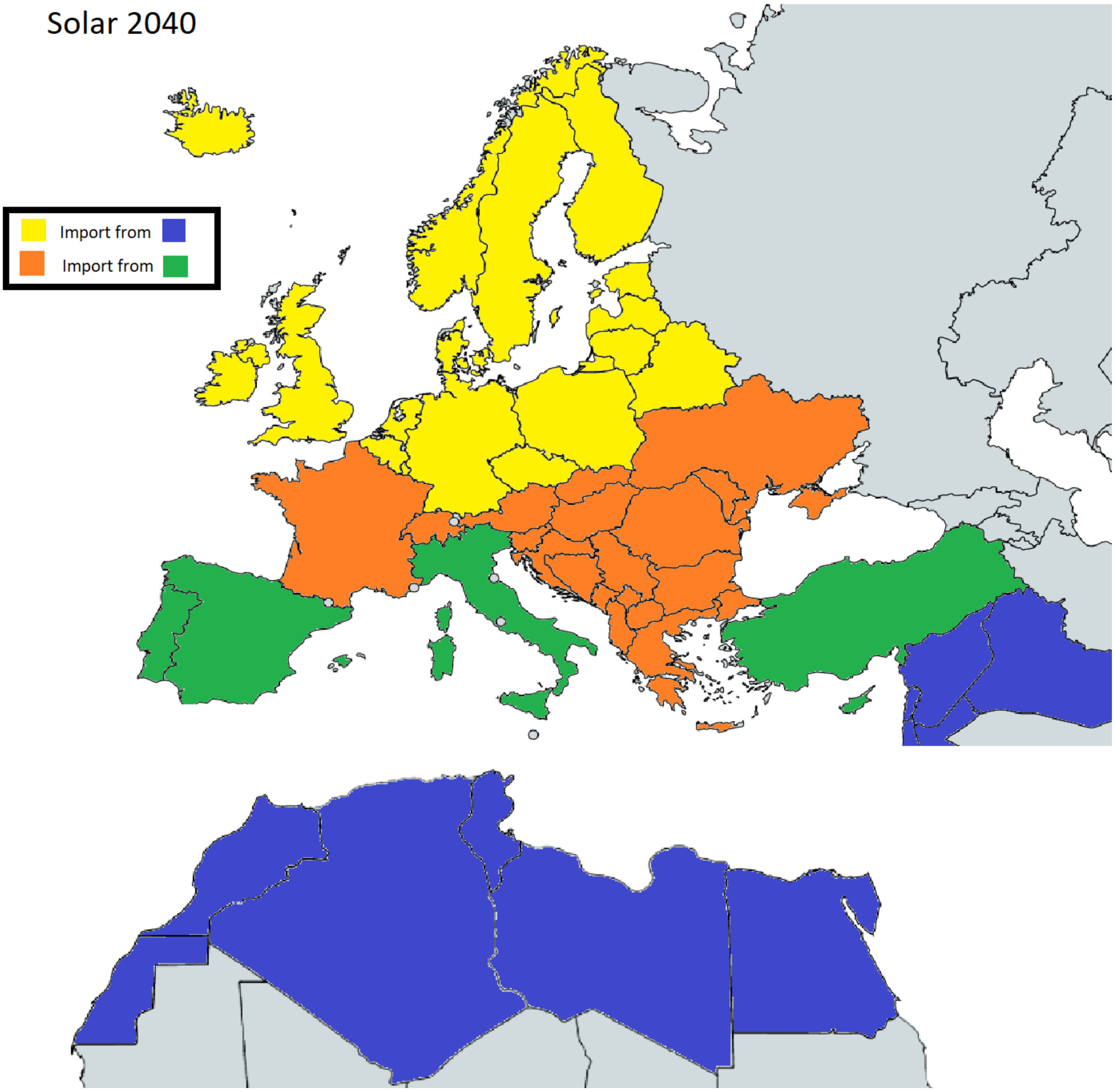


Figure 62 Import and export countries for the solar to hydrogen scenario in 2040. The yellow regions must import from the blue regions. The orange regions must import from the green regions. This is both due to lack of resources and too high prices in the yellow and orange regions.

Table 46 Import and export countries for the solar scenario in 2040

| Import to | Export from |
|---|---|
| Iceland, Ireland, UK, Norway, Sweden, Finland, Estonia, Lithuania, Lativa, Poland, Netherlands, Belgium, Liechtenstein, Denmark, Czech Rep., Belarus, Germany | Western Sahara, Morocco, Algeria, Tunisia, Libya, Egypt, Israel, Iraq, Syria, Jordan, Lebanon |
| France, Switserland, Austria, Hungary, Slovakia, Slovania, Croatia, Bosnia Herzogovina, Serbia, Albania, Montenegro, Greece, Macedonia, Romania, Ukraine, Bulgary, Moldolva | Portugal, Spain, Italy, Turkey |

For the wind energy to hydrogen scenario, the following can be said: There is a lack of potential in the orange and green colored regions. The potential in the yellow regions can be produced at a price low enough for the hydrogen to be transported and stored in the orange regions. This the same for the blue regions exporting green hydrogen to the green colored regions. Iceland is an exception, there is potential for low-cost large scale green hydrogen production but there is no known hydrogen pipeline infrastructure between this region and North-Europe. The abundance of potential in North-Africa can supply Europe when the potential in the yellow regions can't meet the demand anymore. Table 47 shows the green hydrogen import/export system of all countries for wind in 2040.

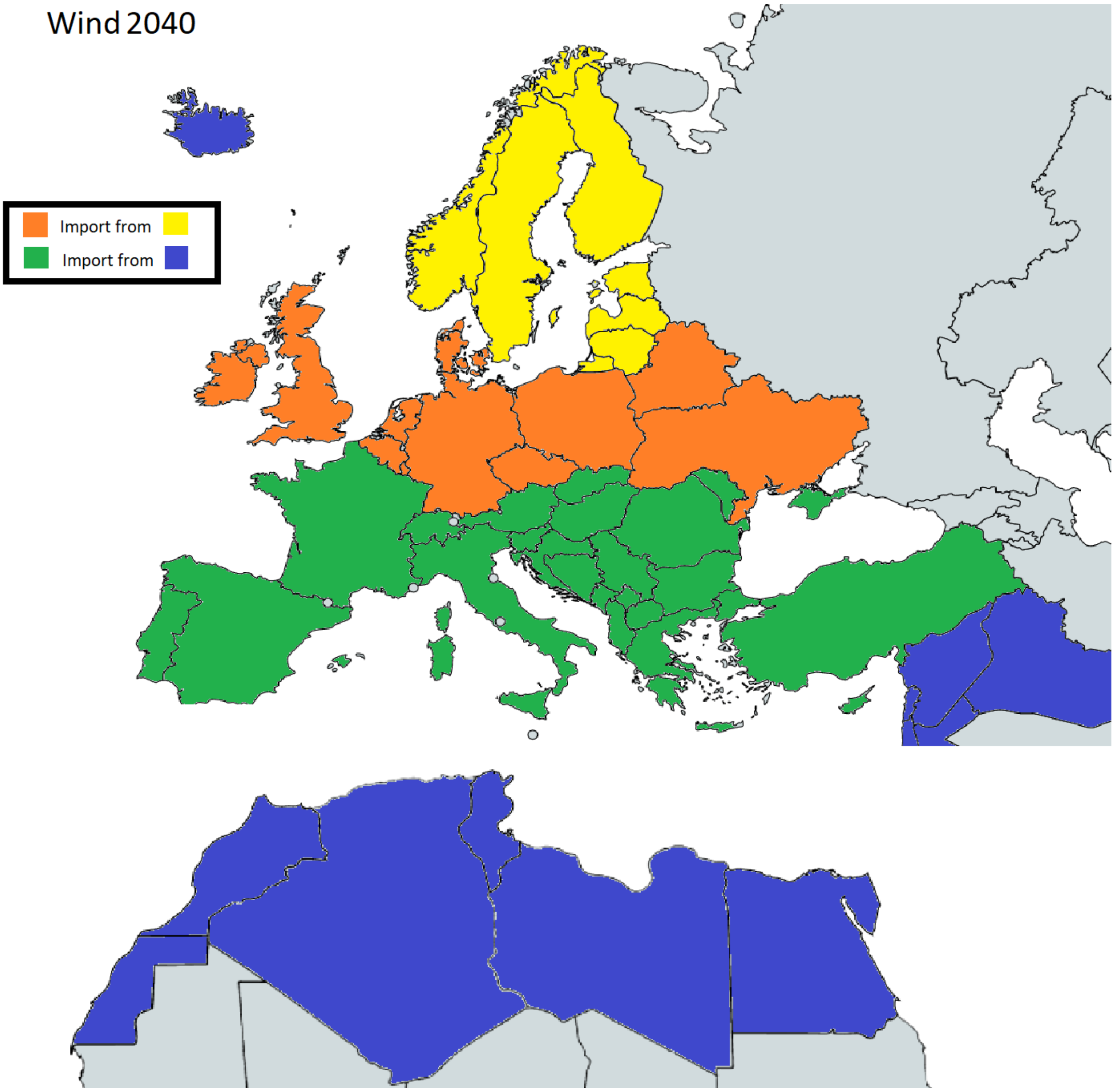


Figure 63 Import and export countries for the wind to hydrogen scenario in 2040. The orange regions must import from the yellow regions. The blue regions must import from the green region. This is both due to lack of resources and/or too high prices.

**Table 47 Import and export countries for the wind scenario in 2040**

| Import to | Export from |
|---|---|
| Ireland, UK, Poland, Netherlands, Belgium, Liechtenstein, Denmark, Czech Rep., Belarus, Poland, Ukraine, Germany | Norway, Sweden, Finland, Estonia, Latvia, Lithuania |
| Portugal, Spain, France, Switserland, Austria, Hungary, Slovakia, Slovania, Croatia, Bosnia Herzogovina, Serbia, Albania, Montenegro, Greece, Macedonia, Romania, Turkey, Bulgary, Moldolva | Western Sahara, Morocco, Algeria, Tunisia, Libya, Egypt, Israel, Iraq, Syria, Jordan, Lebanon |

For the solar and wind combination to hydrogen scenario the following can be said: The amount of potential shown in table 44 depicts that this is the most ideal scenario for large scale low-cost green hydrogen production in 2040. The yellow regions lack potential so this must be imported from the blue regions. The productions costs are low enough in the blue region to allow large distance transport and still hold a competitive price against low carbon hydrogen production with a carbon tax of 0.5 €/kg. The orange regions hold a price of 1.4 €/kg and with storage this price equals 1.5 €/kg, which make producing in these regions competitive with low carbon hydrogen production. However, the orange region is not able to export any green hydrogen as the added transport costs will make the green hydrogen from these regions no longer competitive, as described in table 45. Table 48 shows the green hydrogen import/export system of all countries for solar and wind in 2040.

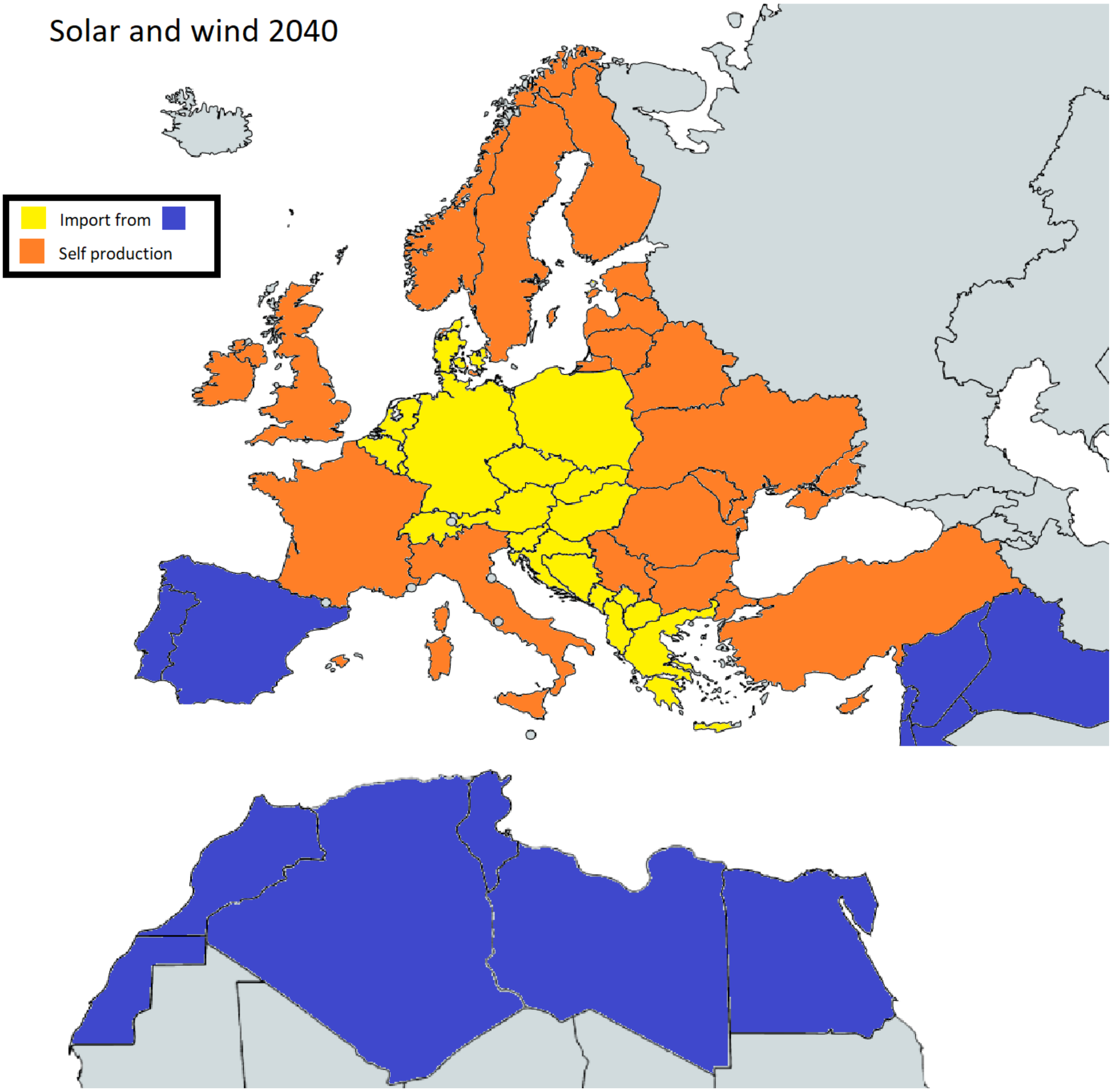


Figure 64 Import and export countries for the solar and wind energy combination to hydrogen in 2040. The yellow regions must import from the blue regions. This is due to lack of resources. The orange countries can produce hydrogen at competitive prices but aren't able to export this due to the increase of the overall price from transport- and storage costs.

Table 48 Import and export countries for the solar and wind scenario in 2040

| Import to | Export from | Self-produce |
|---|---|---|
| Netherlands, Belgium, Liechtenstein, Germany, Switzerland, Czech rep., Austria, Poland, Slovakia, Hungary, Slovenia, Croatia, Bosnia Herzegovina, Montenegro, Greece, Macedonia, | Western Sahara, Morocco, Algeria, Tunisia, Libya, Egypt, Israel, Iraq, Syria, Jordan, Lebanon, Portugal, Spain | Ireland, UK, France, Italy, Norway, Sweden, Finland, Estonia, Latvia, Lithuania, Belarus, Ukraine, Moldova, Romania, Serbia, Bulgaria, Turkey |

Thus, Europe can be partly self-sufficient applying the solar scenario in 2040 but this means that South European countries must export to the Northern European regions. However, it must still import cheap green hydrogen from North African countries to meet the hydrogen demand. With the wind scenario, Europe can’t be self-sufficient according to this research and must import a large portion of its green hydrogen from North African countries. The solar and wind combination shows to be the most promising with almost equal hydrogen potential in North- and South Europe. However, this means that Spain must export large amounts of green hydrogen to Central European countries such as Germany and The Netherlands to sustain a competitive price for these countries. North Africa still holds the lowest prices and highest potential for this scenario and consumes the amount of available space more optimally, but less potential is needed than the previous two scenarios.

The political conclusion is that the European Union has to start investing more in green hydrogen production in order to reduce the dependency on carbon-based energy products in Europe’s future energy system. The amount of $CO_2$ emitted from sectors such as mobility, industry, and Housing & Buildings can be reduced by implementing green hydrogen. In addition, infrastructure is an important sub-factor for the production potential to be transported and stored in order to secure a constant supply of green hydrogen.

# 6 RECOMMENDATIONS

The following recommendations are proposed. Even though large-scale low-cost green hydrogen systems are proposed in this thesis and the results show that there is enough potential found in Europe and North Africa, the technology is there but the size of these large-scale projects is much larger than today renewable electricity projects. Governments companies and financial institutes need to scale up their vision, ambition, and projects to be able to realize a clean renewable energy system.

This research gives a general overview of the production price and -potential and it suggests that research done on a national level gives more insight to the actual potential of green hydrogen production and cost.

Also, it is recommended that the datasets used in ArcGIS Pro are up to date, which enables a more accurate representation of the available areas. Besides this, future research could evaluate the effects of varying input values on the LCOH and production potential to optimize the accuracy of the results. The area needed to produce 1 million tons of green hydrogen differs per renewable energy source and it is recommended to first handle the area size from this research and then iterate this in future research to get more detailed results. This will give a more representative value for the production potential.

Nonetheless, the increasing share of green hydrogen in the energy system will have an overall positive effect on both the energy system and -market. So, it is essential to set up proper regulatory framework to allow a secure and reliable operation, import and export, and transparent market competition.

Demand hubs such as Germany are best to start this type of research on areas with low solar and/or wind electricity prices for close by green hydrogen production to keep the overall productions costs low. It is recommended that this type of research for green hydrogen potential is increased by companies and the European Member States to create an incentive to design, facilitate, and create a hydrogen market, economy, and infrastructure.

It is recommended that this type of research for green hydrogen potential is increased by companies and the European Member States to create an incentive to design, facilitate, and create a hydrogen market, economy, and infrastructure.

In addition, when considering the import and export of hydrogen, it is recommended that governments make it essential to implement green hydrogen production into their future energy policies, and with an emphasis on the cooperation and mutual interest with North Africa. Large scale infrastructure between North Africa and Europe is therefore a must and gives more drive in the development of the green hydrogen market of the future.

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## APPENDIX A COUNTRIES USED IN GIS MODEL

| COUNTRY | Latitude | Longitude | km2 |
|---|---|---|---|
| Albania | 20 | 41 | 28654 |
| Algeria | 3 | 28 | 2317510 |
| Andorra | 2 | 43 | 507 |
| Austria | 14 | 48 | 83946 |
| Belarus | 28 | 54 | 207721 |
| Belgium | 5 | 51 | 30652 |
| Bosnia and Herzegovina | 18 | 44 | 51527 |
| Bulgaria | 25 | 43 | 111023 |
| Cabo Verde | -24 | 16 | 4031 |
| Croatia | 16 | 45 | 55889 |
| Cyprus | 33 | 35 | 9137 |
| Czech Republic | 15 | 50 | 78755 |
| Faroe Islands | -7 | 62 | 1484 |
| Denmark | 10 | 56 | 42711 |
| Egypt | 30 | 26 | 998412 |
| Estonia | 26 | 59 | 45933 |
| Finland | 26 | 65 | 335281 |
| France | 3 | 47 | 548055 |
| Georgia | 44 | 42 | 69957 |
| Germany | 10 | 51 | 357221 |
| Greece | 23 | 39 | 130066 |
| Hungary | 19 | 47 | 92995 |
| Iceland | -19 | 65 | 102952 |
| Iraq | 44 | 33 | 436272 |
| Ireland | -8 | 53 | 69637 |
| Israel | 35 | 31 | 20720 |
| Italy | 12 | 43 | 300077 |
| Jordan | 37 | 31 | 89215 |
| Latvia | 25 | 57 | 64643 |
| Lebanon | 36 | 34 | 10214 |
| Libya | 18 | 27 | 1617580 |
| Liechtenstein | 10 | 47 | 176 |
| Lithuania | 24 | 55 | 65011 |
| Luxembourg | 6 | 50 | 2581 |
| Malta | 14 | 36 | 294 |
| Moldova | 28 | 47 | 33688 |
| Monaco | 7 | 44 | 9 |
| Montenegro | 19 | 43 | 13797 |
| Morocco | -9 | 29 | 672228 |
| Netherlands | 6 | 52 | 34950 |
| North Macedonia | 22 | 42 | 25463 |
| Svalbard | 18 | 79 | 62905 |
| Bouvet Island | 3 | -54 | 57 |
| Norway | 14 | 64 | 320887 |
| Palestinian Territory | 35 | 32 | 6239 |
| Poland | 19 | 52 | 311670 |
| Portugal | -9 | 40 | 91909 |
| Romania | 25 | 46 | 237377 |
| San Marino | 12 | 44 | 60 |
| Serbia | 21 | 44 | 88136 |
| Slovakia | 19 | 49 | 48927 |
| Slovenia | 15 | 46 | 20421 |
| Spain | -3 | 40 | 498657 |
| Canarias | -16 | 28 | 7556 |

| | | | |
|---|---|---|---|
| Sweden | 17 | 63 | 446025 |
| Switzerland | 8 | 47 | 41489 |
| Syria | 39 | 35 | 188006 |
| Tunisia | 10 | 34 | 155382 |
| Turkey | 35 | 39 | 779988 |
| Ukraine | 31 | 49 | 597504 |
| Gibraltar | -5 | 36 | 8 |
| Guernsey | -3 | 49 | 73 |
| Isle of Man | -5 | 54 | 618 |
| Jersey | -2 | 49 | 125 |
| United Kingdom | -3 | 54 | 244349 |
| Vatican City | 12 | 42 | 1 |

## APPENDIX B HYDROGEN PRODUCTION POTENTIAL FOR SOLAR ENERGY IN 2030 AND 2040

Hydrogen production amount for countries in 2030 & 2040 for solar scenario with 500km$^2$ criteria. In addition, the third table depicts the potential for 2040 for a price lower than 1.5€/kg. The fourth table depicts the production potential for the countries with suitable areas with production prices lower than 1.5€/kg.

| | Total Mton Hydrogen | | | | | | | €/kg Hydrogen per Area | | | | | | | Total Mton Hydrogen 2040 | Continent | Continent total Mton |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Country | Area 1 | Area 2 | Area 3 | Area 4 | Area 5 | Area 6 | Area 7 | Area 1 | Area 2 | Area 3 | Area 4 | Area 5 | Area 6 | Area 7 | | | |
| Algeria | | | | 25 | 388 | 9589 | 85 | | | | 1,4 | 1,2 | 1,0 | 0,9 | 10087 | NA | NA = 26179 Mton hydrogen |
| Belarus | | 163 | | | | | | | 2,1 | | | | | | 163 | EU | EU = 2255 Mton hydrogen |
| Bosnia and Herzegovina | | | 5 | | | | | | | 1,9 | | | | | 5 | EU | |
| Bulgaria | | | 13 | | | | | | | 1,9 | | | | | 13 | EU | |
| Cabo Verde | | | | | 2 | | | | | | | 1,2 | | | 2 | EU | |
| Egypt | | | | | | 3207 | 779 | | | | | | 1,0 | 0,9 | 3986 | NA | |
| Estonia | | 54 | | | | | | | 2,1 | | | | | | 54 | EU | |
| France | | | 10 | 2 | | | | | | 1,9 | 1,4 | | | | 12 | EU | |
| Georgia | | | 7 | 4 | | | | | | 1,9 | 1,4 | | | | 11 | EU | |
| Greece | | | | 5 | | | | | | | 1,4 | | | | 5 | EU | |
| Iraq | | | | | 873 | 514 | | | | | | 1,2 | 1,0 | | 1387 | NA | |
| Israel | | | | | | 10 | | | | | | | 1,0 | | 10 | NA | |
| Italy | | | | 78 | 11 | | | | | | 1,4 | 1,2 | | | 89 | EU | |
| Jordan | | | | | 2 | 242 | 65 | | | | | 1,2 | 1,0 | 0,9 | 309 | NA | |
| Latvia | | 40 | | | | | | | 2,1 | | | | | | 40 | EU | |
| Libya | | | | | 68 | 6440 | 1083 | | | | | 1,2 | 1,0 | 0,9 | 7590 | NA | |
| Lithuania | | 34 | | | | | | | 2,1 | | | | | | 34 | EU | |
| Moldova | | | 11 | | | | | | | 1,9 | | | | | 11 | EU | |
| Morocco | | | | | 209 | 1776 | 3 | | | | | 1,2 | 1,0 | 0,9 | 1988 | NA | |
| Norway | 5 | 28 | | | | | | 2,7 | 2,1 | | | | | | 33 | EU | |
| Portugal | | | | 30 | 72 | | | | | | 1,4 | 1,2 | | | 102 | EU | |
| Romania | | 2 | 104 | | | | | | 2,1 | 1,9 | | | | | 106 | EU | |
| Serbia | | | 20 | | | | | | | 1,9 | | | | | 20 | EU | |
| Spain | | | 20 | 87 | 268 | | | | | 1,9 | 1,4 | 1,2 | | | 375 | EU | |
| Sweden | 28 | 119 | | | | | | 2,7 | 2,1 | | | | | | 147 | EU | |
| Syria | | | | | 238 | 277 | | | | | | 1,2 | 1,0 | | 515 | NA | |
| Tunisia | | | | | 74 | 234 | | | | | | 1,2 | 1,0 | | 307 | NA | |
| Turkey | | | 18 | 220 | 282 | | | | | 1,9 | 1,4 | 1,2 | | | 520 | EU | |
| Ukraine | | 167 | 318 | | | | | | 2,1 | 1,9 | | | | | 485 | EU | |
| United Kingdom | 27 | | | | | | | 2,7 | | | | | | | 27 | EU | |

|  | Total Mton Hydrogen |  |  |  |  |  |  | €/kg Hydrogen per area |  |  |  |  |  |  | Total Mton Hydrogen 2030 | Continent | Continent total Mton |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Country | *Area 1* | *Area 2* | *Area 3* | *Area 4* | *Area 5* | *Area 6* | *Area 7* | *Area 1* | *Area 2* | *Area 3* | *Area 4* | *Area 5* | *Area 6* | *Area 7* |  |  |  |
| Algeria |  |  |  | 21 | 325 | 8022 | 71 |  |  |  | 2,4 | 2,1 | 1,8 | 1,6 | 8438 | NA | NA = 21900 Mton hydrogen |
| Belarus |  | 137 |  |  |  |  |  |  | 3,5 |  |  |  |  |  | 137 | EU | EU = 1886 Mton hydrogen |
| Bosnia and Herzegovina |  |  | 4 |  |  |  |  |  |  | 2,8 |  |  |  |  | 4 | EU |  |
| Bulgaria |  |  | 11 |  |  |  |  |  |  | 2,8 |  |  |  |  | 11 | EU |  |
| Cabo Verde |  |  |  |  | 2 |  |  |  |  |  |  | 2,1 |  |  | 2 | EU |  |
| Egypt |  |  |  |  |  | 2683 | 652 |  |  |  |  |  | 1,8 | 1,6 | 3334 | NA |  |
| Estonia |  | 46 |  |  |  |  |  |  | 3,5 |  |  |  |  |  | 46 | EU |  |
| France |  |  | 8 | 2 |  |  |  |  |  | 2,8 | 2,4 |  |  |  | 10 | EU |  |
| Georgia |  |  | 6 | 3 |  |  |  |  |  | 2,8 | 2,4 |  |  |  | 9 | EU |  |
| Greece |  |  |  | 4 |  |  |  |  |  |  | 2,4 |  |  |  | 4 | EU |  |
| Iraq |  |  |  |  | 730 | 430 |  |  |  |  |  | 2,1 | 1,8 |  | 1160 | NA |  |
| Israel |  |  |  |  |  | 9 |  |  |  |  |  |  | 1,8 |  | 9 | NA |  |
| Italy |  |  |  | 65 | 9 |  |  |  |  |  | 2,4 | 2,1 |  |  | 74 | EU |  |
| Jordan |  |  |  |  | 2 | 202 | 54 |  |  |  |  | 2,1 | 1,8 | 1,6 | 258 | NA |  |
| Latvia |  | 34 |  |  |  |  |  |  | 3,5 |  |  |  |  |  | 34 | EU |  |
| Libya |  |  |  |  | 57 | 5387 | 906 |  |  |  |  | 2,1 | 1,8 | 1,6 | 6350 | NA |  |
| Lithuania |  | 29 |  |  |  |  |  |  | 3,5 |  |  |  |  |  | 29 | EU |  |
| Moldova |  |  | 10 |  |  |  |  |  |  | 2,8 |  |  |  |  | 10 | EU |  |
| Morocco |  |  |  |  | 175 | 1486 | 2 |  |  |  |  | 2,1 | 1,8 | 1,6 | 1663 | NA |  |
| Norway | 4 | 23 |  |  |  |  |  | 4,6 | 3,5 |  |  |  |  |  | 28 | EU |  |
| Portugal |  |  |  | 25 | 61 |  |  |  |  |  | 2,4 | 2,1 |  |  | 85 | EU |  |
| Romania |  | 2 | 87 |  |  |  |  |  | 3,5 | 2,8 |  |  |  |  | 89 | EU |  |
| Serbia |  |  | 17 |  |  |  |  |  |  | 2,8 |  |  |  |  | 17 | EU |  |
| Spain |  |  | 17 | 73 | 224 |  |  |  |  | 2,8 | 2,4 | 2,1 |  |  | 314 | EU |  |
| Sweden | 24 | 99 |  |  |  |  |  | 4,6 | 3,5 |  |  |  |  |  | 123 | EU |  |
| Syria |  |  |  |  | 199 | 232 |  |  |  |  |  | 2,1 | 1,8 |  | 431 | NA |  |
| Tunisia |  |  |  |  | 62 | 195 |  |  |  |  |  | 2,1 | 1,8 |  | 257 | NA |  |
| Turkey |  |  | 15 | 184 | 236 |  |  |  |  | 2,8 | 2,4 | 2,1 |  |  | 435 | EU |  |
| Ukraine |  | 140 | 266 |  |  |  |  |  | 3,5 | 2,8 |  |  |  |  | 406 | EU |  |
| United Kingdom | 22 |  |  |  |  |  |  | 4,6 |  |  |  |  |  |  | 22 | EU |  |

SOLAR 2040 <1.5 €/kg

| | **Total Mton Hydrogen** | | | | €/kg Hydrogen per area | | | | Total Mton Hydrogen 2040 |
|---|---|---|---|---|---|---|---|---|---|
| Country | Area 4 | Area 5 | Area 6 | Area 7 | Area 4 | Area 5 | Area 6 | Area 7 | 27241 |
| Algeria | 25 | 388 | 9589 | 85 | 1,4 | 1,2 | 1,0 | 0,9 | 10087 |
| Cabo Verde | | 2 | | | | 1,2 | | | 2 |
| Egypt | | | 3207 | 779 | | | 1,0 | 0,9 | 3986 |
| France | 2 | | | | 1,4 | | | | 2 |
| Georgia | 4 | | | | 1,4 | | | | 4 |
| Greece | 5 | | | | 1,4 | | | | 5 |
| Iraq | | 873 | 514 | | | 1,2 | 1,0 | | 1387 |
| Israel | | | 10 | | | | 1,0 | | 10 |
| Italy | 78 | 11 | | | 1,4 | 1,2 | | | 89 |
| Jordan | | 2 | 242 | 65 | | 1,2 | 1,0 | 0,9 | 309 |
| Libya | | 68 | 6440 | 1083 | | 1,2 | 1,0 | 0,9 | 7590 |
| Morocco | | 209 | 1776 | 3 | | 1,2 | 1,0 | 0,9 | 1988 |
| Portugal | 30 | 72 | | | 1,4 | 1,2 | | | 102 |
| Spain | 87 | 268 | | | 1,4 | 1,2 | | | 355 |
| Syria | | 238 | 277 | | | 1,2 | 1,0 | | 515 |
| Tunisia | | 74 | 234 | | | 1,2 | 1,0 | | 307 |
| Turkey | 220 | 282 | | | 1,4 | 1,2 | | | 502 |

| Land | km2 for H2 production | Total km2 Land | % of total land used for H2 production | Energy Consumption GWh/yr | Mton H2 production 2040 | Energy from H2 (GWh/yr) | % Electricity consumption supply by H2 |
|---|---|---|---|---|---|---|---|
| Algeria | 2030424 | 2381741 | 85% | 62062 | 11293,11 | 444948348 | 716942% |
| Belarus | 66582 | 202900 | 33% | 32736 | 272,44 | 10734215 | 32790% |
| Bosnia and Herzegovina | 1472 | 51187 | 3% | 12253 | 18,41 | 725167 | 5918% |
| Bulgaria | 4127 | 108612 | 4% | 33134 | 11,15 | 439198 | 1326% |
| Cabo Verde | 536 | 4033 | 13% | 455 | 2,81 | 110785 | 24348% |
| Egypt | 777408 | 995450 | 78% | 150579 | 4429,08 | 174505729 | 115890% |
| Estonia | 22219 | 42388 | 52% | 8858 | 76,71 | 3022417 | 34121% |
| France | 3708 | 640427 | 1% | 449422 | 436,95 | 17215925 | 3831% |
| Georgia | 3245 | 69700 | 5% | 12179 | 8,40 | 330848 | 2717% |
| Greece | 1355 | 130647 | 1% | 53635 | 44,14 | 1739222 | 3243% |
| Iraq | 303294 | 437367 | 69% | 43971 | 1621,35 | 63881254 | 145280% |
| Israel | 2423 | 20330 | 12% | 56391 | 9,64 | 379885 | 674% |
| Italy | 23185 | 294140 | 8% | 297150 | 61,20 | 2411354 | 811% |
| Jordan | 60202 | 88802 | 68% | 17384 | 338,67 | 13343569 | 76758% |
| Latvia | 16337 | 62249 | 26% | 6877 | 85,67 | 3375309 | 49081% |
| Libya | 1493071 | 1759540 | 85% | 25693 | 8568,61 | 337603307 | 1313989% |
| Lithuania | 13966 | 62680 | 22% | 11306 | 73,94 | 2913170 | 25767% |
| Moldova | 3630 | 32891 | 11% | 5957 | 16,72 | 658761 | 11059% |
| Morocco | 404084 | 446300 | 91% | 29678 | 2409,06 | 94916931 | 319823% |
| Norway | 14010 | 33893 | 41% | 110682 | 4,98 | 196130 | 177% |
| Portugal | 24471 | 91119 | 27% | 48035 | 101,12 | 3984096 | 8294% |
| Romania | 34070 | 231291 | 15% | 55008 | 109,77 | 4324920 | 7862% |
| Serbia | 6320 | 88246 | 7% | 30292 | 49,88 | 1965294 | 6488% |
| Spain | 91101 | 498980 | 18% | 241563 | 364,17 | 14348162 | 5940% |
| Sweden | 63156 | 410335 | 15% | 131798 | 216,40 | 8526280 | 6469% |
| Syria | 110076 | 183630 | 60% | 14263 | 561,89 | 22138485 | 155216% |
| Tunisia | 63842 | 155360 | 41% | 15838 | 380,74 | 15001229 | 94717% |
| Turkey | 128994 | 769632 | 17% | 251376 | 270,56 | 10660222 | 4241% |
| Ukraine | 169474 | 579300 | 29% | 128806 | 904,98 | 35656402 | 27682% |
| United Kingdom | 13852 | 241930 | 6% | 300520 | 29,20 | 1150666 | 383% |

# APPENDIX C HYDROGEN PRODUCTION POTENTIAL FOR WIND ENERGY IN 2030 AND 2040

Hydrogen production amount for countries in 2030 & 2040 for wind scenario 1000km$^2$ criteria. In addition, the third table depicts the potential for 2040 for a price lower than 1.5€/kg. The fourth table depicts the production potential for the countries with suitable areas with production prices lower than 1.5€/kg.

| | Total Mton Hydrogen | | | | | | | €/kg Hydrogen per area | | | | | | | Total Mton Hydrogen 2040 | Continent | Continent total Mton |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Country | *Area 1* | *Area 2* | *Area 3* | *Area 4* | *Area 5* | *Area 6* | *Area 7* | *Area 1* | *Area 2* | *Area 3* | *Area 4* | *Area 5* | *Area 6* | *Area 7* | | | |
| Algeria | 2 | 29 | | 627 | 367 | 52 | | 3,5 | 2,5 | | 1,5 | 1,2 | 1,1 | | 1078 | NA | NA = 2822 Mton hydrogen |
| Egypt | 1 | 12 | 1 | 184 | 139 | 27 | 1 | 3,5 | 2,5 | 2,5 | 1,5 | 1,2 | 1,1 | 1,0 | 366 | NA | EU = 82 Mton hydrogen |
| Iceland | | | 1 | | 1 | 5 | 1 | | | 2,5 | | 1,2 | 1,1 | 1,0 | 9 | EU | |
| Iraq | 1 | 4 | | 120 | 4 | | | 3,5 | 2,5 | | 1,5 | 1,2 | | | 128 | NA | |
| Libya | 1 | 6 | | 617 | 264 | 10 | | 3,5 | 2,5 | | 1,5 | 1,2 | 1,1 | | 898 | NA | |
| Morocco | 1 | 5 | 52 | 18 | 27 | 107 | 78 | 3,5 | 2,5 | 2,5 | 1,5 | 1,2 | 1,1 | 1,0 | 288 | NA | |
| Svalbard | | | | | | 2 | | | | | | | 1,1 | | 2 | EU | |
| Sweden | | 9 | | 6 | 3 | | | | 2,5 | | 1,5 | 1,2 | | | 17 | EU | |
| Syria | | 0 | | 13 | 3 | 1 | | | 2,5 | | 1,5 | 1,2 | 1,1 | | 18 | NA | |
| Tunisia | | | | 15 | 19 | | | | | | 1,5 | 1,2 | | | 34 | NA | |
| Belarus | | | | 4 | | | | | | | 1,8 | | | | 4 | EU | |
| Finland | | 3 | | 4 | | | | | 2,5 | | 1,8 | | | | 6 | EU | |
| Jordan | | 2 | | 10 | | | | | 2,5 | | 1,5 | | | | 11 | NA | |
| Latvia | | | | 3 | | | | | | | 1,8 | | | | 3 | EU | |
| Lithuania | | | | 3 | | | | | | | 1,8 | | | | 3 | EU | |
| Norway | | | | 3 | | | | | | | 1,5 | | | | 3 | EU | |
| Ukraine | | | | 26 | | | | | | | 2,5 | | | | 26 | EU | |
| Portugal | | 4 | | | | | | | 2,5 | | | | | | 4 | EU | |
| Romania | | 0 | | | | | | | 2,5 | | | | | | 0 | EU | |
| Spain | 0 | 1 | | | | | | 3,5 | 2,5 | | | | | | 2 | EU | |
| Turkey | 2 | 1 | | | | | | 3,5 | 2,5 | | | | | | 3 | EU | |

| | **Total Mton Hydrogen** | | | | | | | **€/kg Hydrogen per area** | | | | | | | **Total Mton Hydrogen 2030** | **Continent** | **Continent total Mton** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Country | *Area 1* | *Area 2* | *Area 3* | *Area 4* | *Area 5* | *Area 6* | *Area 7* | *Area 1* | *Area 2* | *Area 3* | *Area 4* | *Area 5* | *Area 6* | *Area 7* | | | |
| Algeria | 2 | 21 | | 457 | 268 | 38 | | 5,3 | 3,8 | | 2,3 | 1,9 | 1,7 | | 786 | NA | NA = 1552 Mton hydrogen |
| Belarus | | | | 3 | | | | | | | 2,8 | | | | 3 | NA | EU = 564 Mton hydrogen |
| Egypt | 1 | 9 | 1 | 134 | 102 | 20 | 1 | 5,3 | 3,8 | 3,8 | 2,3 | 1,9 | 1,7 | 1,5 | 266 | EU | |
| Finland | | 2 | | 3 | | | | | 3,8 | | 2,8 | | | | 5 | NA | |
| Iceland | | | 1 | | 1 | 4 | 1 | | | 3,8 | | 1,9 | 1,7 | 1,5 | 6 | NA | |
| Iraq | 0 | 3 | | 88 | 3 | | | 5,3 | 3,8 | | 2,3 | 1,9 | | | 93 | NA | |
| Jordan | | 1 | | 7 | | | | | 3,8 | | 2,3 | | | | 8 | EU | |
| Latvia | | | | 2 | | | | | | | 2,8 | | | | 2 | EU | |
| Libya | 1 | 4 | | 450 | 193 | 7 | | 5,3 | 3,8 | | 2,3 | 1,9 | 1,7 | | 654 | NA | |
| Lithuania | | | | 2 | | | | | | | 2,8 | | | | 2 | NA | |
| Morocco | 1 | 4 | 38 | 13 | 19 | 78 | 57 | 5,3 | 3,8 | 3,8 | 2,3 | 1,9 | 1,7 | 1,5 | 210 | EU | |
| Norway | | | | 2 | | | | | | | 2,3 | | | | 2 | EU | |
| Portugal | | 3 | | | | | | | 3,8 | | | | | | 3 | NA | |
| Romania | | 0 | | | | | | | 3,8 | | | | | | 0 | EU | |
| Spain | 0 | 1 | | | | | | 5,3 | 3,8 | | | | | | 1 | EU | |
| Svalbard | | | | | | 2 | | | | | | | 1,7 | | 2 | EU | |
| Sweden | | 6 | | 4 | 2 | | | | 3,8 | | 2,3 | 1,9 | | | 13 | EU | |
| Syria | | 0 | | 10 | 2 | 1 | | | 3,8 | | 2,3 | 1,9 | 1,7 | | 13 | EU | |
| Tunisia | | | | 11 | 14 | | | | | | 2,3 | 1,9 | | | 25 | EU | |
| Turkey | 1 | 1 | | | | | | 5,3 | 3,8 | | | | | | 2 | EU | |
| Ukraine | | | | 19 | | | | | | | 3,8 | | | | 19 | EU | |

WIND 2040 <1.5 €/kg

| | **Total Mton Hydrogen** | | | | **€/kg Hydrogen per area** | | | | **Total Mton Hydrogen 2040** |
|---|---|---|---|---|---|---|---|---|---|
| Country | Area 4 | Area 5 | Area 6 | Area 7 | Area 4 | Area 5 | Area 6 | Area 7 | 2726 |
| Algeria | 627 | 367 | 52 | | 1,5 | 1,2 | 1,1 | | 1047 |
| Egypt | 184 | 139 | 27 | 1 | 1,5 | 1,2 | 1,1 | 1,0 | 352 |
| Iceland | | 1 | 5 | 1 | | 1,2 | 1,1 | 1,0 | 8 |
| Iraq | 120 | 4 | | | 1,5 | 1,2 | | | 124 |
| Libya | 617 | 264 | 10 | | 1,5 | 1,2 | 1,1 | | 891 |
| Morocco | 18 | 27 | 107 | 78 | 1,5 | 1,2 | 1,1 | 1,0 | 230 |
| Svalbard | | | 2 | | | | 1,1 | | 2 |
| Sweden | 6 | 3 | | | 1,5 | 1,2 | | | 9 |
| Syria | 13 | 3 | 1 | | 1,5 | 1,2 | 1,1 | | 18 |
| Tunisia | 15 | 19 | | | 1,5 | 1,2 | | | 34 |
| Jordan | 10 | | | | 1,5 | | | | 10 |
| Norway | 3 | | | | 1,5 | | | | 3 |

WIND 2030 <1.5 €/kg

| | **Total Mton Hydrogen** | | | | **€/kg Hydrogen per area** | | | | **Total Mton Hydrogen 2040** |
|---|---|---|---|---|---|---|---|---|---|
| Country | Area 4 | Area 5 | Area 6 | Area 7 | Area 4 | Area 5 | Area 6 | Area 7 | 59 |
| Egypt | | | | 1 | | | | 1,5 | 1 |
| Iceland | | | | 1 | | | | 1,5 | 1 |
| Marocco | | | | 57 | | | | 1,5 | 57 |

| Land | km2 for H2 production | Total km2 Land | % of total land used for H2 production | Energy Consumption GWh/yr | Mton H2 production 2040 | Energy from H2 (GWh/yr) | % Electricity consumption supply by H2 |
|---|---|---|---|---|---|---|---|
| Algeria | 1457560 | 2381741 | 61% | 62062 | 1078,04 | 42474877 | 68439% |
| Belarus | 5666 | 202900 | 3% | 32736 | 3,51 | 138274 | 422% |
| Egypt | 490093 | 995450 | 49% | 150579 | 365,39 | 14396274 | 9561% |
| Finland | 10910 | 303816 | 4% | 84207 | 5,89 | 231934 | 275% |
| Iceland | 10161 | 100250 | 10% | 18679 | 8,42 | 331712 | 1776% |
| Iraq | 183673 | 437367 | 42% | 43971 | 128,03 | 5044260 | 11472% |
| Jordan | 17385 | 88802 | 20% | 17384 | 11,38 | 448514 | 2580% |
| Latvia | 4039 | 62249 | 6% | 6877 | 2,50 | 98568 | 1433% |
| Libya | 1217434 | 1759540 | 69% | 25693 | 897,74 | 35371024 | 137668% |
| Lithuania | 4315 | 62680 | 7% | 11306 | 2,67 | 105304 | 931% |
| Morocco | 361452 | 446300 | 81% | 29678 | 275,78 | 10865827 | 36612% |
| Norway | 3608 | 33893 | 11% | 110682 | 2,55 | 100629 | 91% |
| Portugal | 8789 | 91119 | 10% | 48035 | 4,15 | 163439 | 340% |
| Romania | 977 | 231291 | 0% | 55008 | 0,46 | 18168 | 33% |
| Spain | 4344 | 498980 | 1% | 241563 | 1,89 | 74311 | 31% |
| Svalbard | 2362 | 61022 | 4% | UNKNOWN | 2,09 | 82346 |  |
| Sweden | 30016 | 410335 | 7% | 131798 | 17,22 | 678485 | 515% |
| Syria | 25108 | 183630 | 14% | 14263 | 18,25 | 718965 | 5041% |
| Tunisia | 44706 | 155360 | 29% | 15838 | 34,38 | 1354378 | 8551% |
| Turkey | 7215 | 769632 | 1% | 251376 | 2,90 | 114362 | 45% |
| Ukraine | 37057 | 579300 | 6% | 128806 | 17,49 | 689109 | 535% |

# APPENDIX D HYDROGEN PRODUCTION POTENTIAL FOR THE SOLAR AND WIND ENERGY COMBINATION IN 2030 AND 2040

Hydrogen production amount for countries in 2030 & 2040 for Solar&Wind scenario 500km$^2$ criteria. In addition, the third table depicts the potential for 2040 for a price lower than 1.5€/kg. The fourth table depicts the production potential for the countries with suitable areas with production prices lower than 1.5€/kg.

| | **Total Mton Hydrogen** | | | | | | **€/kg Hydrogen per area** | | | | | | **Total Mton Hydrogen 2040** | **Continent** | **Continent total Mton** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Country | *Area 2* | *Area 3* | *Area 4* | *Area 5* | *Area 6* | *Area 7* | *Area 2* | *Area 3* | *Area 4* | *Area 5* | *Area 6* | *Area 7* | | | |
| Algeria | | 57 | 536 | 5699 | 2807 | 4 | | 1,4 | 1,1 | 1,0 | 0,8 | 0,7 | 9103 | NA | NA = 24000 Mton hydrogen |
| Belarus | | 424 | | | | | | 1,4 | | | | | 424 | EU | EU = 2840 Mton hydrogen |
| Bulgaria | 3 | 46 | | | | | 1,8 | 1,4 | | | | | 49 | EU | |
| Cyprus | | 8 | | | | | | 1,4 | | | | | 8 | EU | |
| Egypt | | | 165 | 1988 | 1425 | 48 | | | 1,1 | 1,0 | 0,8 | 0,7 | 3626 | NA | |
| Estonia | | 139 | 3 | | | | | 1,4 | 1,1 | | | | 143 | EU | |
| France | | 48 | | | | | | 1,4 | | | | | 48 | EU | |
| Hungary | | 5 | | | | | | 1,4 | | | | | 5 | EU | |
| Iraq | | 20 | 213 | 1095 | | | | 1,4 | 1,1 | 1,0 | | | 1328 | NA | |
| Italy | | 97 | 7 | | | | | 1,4 | 1,1 | | | | 104 | EU | |
| Jordan | | | 21 | 245 | | | | | 1,1 | 1,0 | | | 266 | NA | |
| Latvia | | 119 | | | | | | 1,4 | | | | | 119 | EU | |
| Libya | | | 57 | 4805 | 2256 | 32 | | | 1,1 | 1,0 | 0,8 | 0,7 | 7151 | NA | |
| Lithuania | | 124 | | | | | | 1,4 | | | | | 124 | EU | |
| Moldova | | 18 | | | | | | 1,4 | | | | | 18 | EU | |
| Morocco | | 28 | 129 | 282 | 829 | 517 | | 1,4 | 1,1 | 1,0 | 0,8 | 0,7 | 1785 | NA | |
| Portugal | | 32 | 54 | | | | | 1,4 | 1,1 | | | | 86 | EU | |
| Romania | 4 | 146 | | | | | 1,8 | 1,4 | | | | | 150 | EU | |
| Serbia | | 34 | | | | | | 1,4 | | | | | 34 | EU | |
| Spain | | 167 | 130 | | | | | 1,4 | 1,1 | | | | 296 | EU | |
| Sweden | 11 | 308 | 17 | | | | 1,8 | 1,4 | 1,1 | | | | 336 | EU | |
| Syria | | 18 | 159 | 252 | 23 | | | 1,4 | 1,1 | 1,0 | 0,8 | | 453 | NA | |
| Tunisia | | 2 | 29 | 116 | 133 | | | 1,4 | 1,1 | 1,0 | 0,8 | | 280 | NA | |
| Turkey | | 108 | 37 | | | | | 1,4 | 1,1 | | | | 146 | EU | |
| Ukraine | | 503 | 173 | | | | | 1,4 | 1,1 | | | | 676 | EU | |
| United Kingdom | | 46 | | | | | | 1,4 | | | | | 46 | EU | |
| Israel | | | 8 | | | | | | 1,1 | | | | 8 | NA | |
| Greece | | 2 | | | | | | 1,4 | | | | | 2 | EU | |
| Norway | | 24 | | | | | | 1,4 | | | | | 24 | EU | |
| Poland | | 3 | | | | | | 1,4 | | | | | 3 | EU | |

| | **Total Mton Hydrogen** | | | | | | | **€/kg Hydrogen per area** | | | | | | | **Total Mton Hydrogen 2030** | **Continent** | **Continent total Mton** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Country | *Area 2* | *Area 3* | *Area 4* | *Area 5* | *Area 6* | *Area 7* | | | *Area 2* | *Area 3* | *Area 4* | *Area 5* | *Area 6* | *Area 7* | | | |
| Algeria | | 47 | 440 | 4672 | 2302 | 3 | | | | 2,8 | 2,3 | 1,9 | 1,7 | 1,5 | 7465 | NA | NA = 19681 Mton hydrogen |
| Belarus | | 348 | | | | | | | | 2,8 | | | | | 348 | EU | EU = 2330 Mton hydrogen |
| Bulgaria | 2 | 38 | | | | | | | 3,7 | 2,8 | | | | | 40 | EU | |
| Cyprus | | 7 | | | | | | | | 2,8 | | | | | 7 | EU | |
| Egypt | | | 135 | 1630 | 1169 | 40 | | | | | 2,3 | 1,9 | 1,7 | 1,5 | 2974 | NA | |
| Estonia | | 114 | 3 | | | | | | | 2,8 | 2,3 | | | | 117 | EU | |
| France | | 40 | | | | | | | | 2,8 | | | | | 40 | EU | |
| Greece | | 2 | | | | | | | | 2,8 | | | | | 2 | EU | |
| Hungary | | 4 | | | | | | | | 2,8 | | | | | 4 | EU | |
| Iraq | | 17 | 175 | 898 | | | | | | 2,8 | 2,3 | 1,9 | | | 1089 | NA | |
| Israel | | | 6 | | | | | | | | 2,3 | | | | 6 | NA | |
| Italy | | 80 | 5 | | | | | | | 2,8 | 2,3 | | | | 85 | EU | |
| Jordan | | | 17 | 201 | | | | | | | 2,3 | 1,9 | | | 218 | NA | |
| Latvia | | 97 | | | | | | | | 2,8 | | | | | 97 | EU | |
| Libya | | | 47 | 3940 | 1851 | 26 | | | | | 2,3 | 1,9 | 1,7 | 1,5 | 5864 | NA | |
| Lithuania | | 102 | | | | | | | | 2,8 | | | | | 102 | EU | |
| Moldova | | 15 | | | | | | | | 2,8 | | | | | 15 | EU | |
| Morocco | | 23 | 106 | 231 | 680 | 424 | | | | 2,8 | 2,3 | 1,9 | 1,7 | 1,5 | 1465 | NA | |
| Norway | | 20 | | | | | | | | 2,8 | | | | | 20 | EU | |
| Poland | | 2 | | | | | | | | 2,8 | | | | | 2 | EU | |
| Portugal | | 26 | 44 | | | | | | | 2,8 | 2,3 | | | | 70 | EU | |
| Romania | 4 | 119 | | | | | | | 3,7 | 2,8 | | | | | 123 | EU | |
| Serbia | | 28 | | | | | | | | 2,8 | | | | | 28 | EU | |
| Spain | | 137 | 107 | | | | | | | 2,8 | 2,3 | | | | 243 | EU | |
| Sweden | 9 | 253 | 14 | | | | | | 3,7 | 2,8 | 2,3 | | | | 276 | EU | |
| Syria | | 15 | 131 | 207 | 19 | | | | | 2,8 | 2,3 | 1,9 | 1,7 | | 371 | NA | |
| Tunisia | | 2 | 24 | 95 | 109 | | | | | 2,8 | 2,3 | 1,9 | 1,7 | | 229 | NA | |
| Turkey | | 89 | 31 | | | | | | | 2,8 | 2,3 | | | | 120 | EU | |
| Ukraine | | 413 | 142 | | | | | | | 2,8 | 2,3 | | | | 555 | EU | |
| United Kingdom | | 38 | | | | | | | | 2,8 | | | | | 38 | EU | |

SOLAR&WIND 2040 <1.5 €/kg

| | **Total Mton Hydrogen** | | | | | **€/kg Hydrogen per area** | | | | | **Total Mton Hydrogen 2040** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Country | *Area 3* | *Area 4* | *Area 5* | *Area 6* | *Area 7* | *Area 3* | *Area 4* | *Area 5* | *Area 6* | *Area 7* | 26821 |
| Algeria | 57 | 536 | 5699 | 2807 | 4 | 1,4 | 1,1 | 1 | 0,8 | 0,7 | 9103 |
| Belarus | 424 | | | | | 1,4 | | | | | 424 |
| Bulgaria | 46 | | | | | 1,4 | | | | | 46 |
| Cyprus | 8 | | | | | 1,4 | | | | | 8 |
| Egypt | | 165 | 1988 | 1425 | 48 | | 1,1 | 1 | 0,8 | 0,7 | 3626 |
| Estonia | 139 | 3 | | | | 1,4 | 1,1 | | | | 143 |
| France | 48 | | | | | 1,4 | | | | | 48 |
| Hungary | 5 | | | | | 1,4 | | | | | 5 |
| Iraq | 20 | 213 | 1095 | | | 1,4 | 1,1 | 1 | | | 1328 |
| Italy | 97 | 7 | | | | 1,4 | 1,1 | | | | 104 |
| Jordan | | 21 | 245 | | | | 1,1 | 1 | | | 266 |
| Latvia | 119 | | | | | 1,4 | | | | | 119 |
| Libya | | 57 | 4805 | 2256 | 32 | | 1,1 | 1 | 0,8 | 0,7 | 7151 |
| Lithuania | 124 | | | | | 1,4 | | | | | 124 |
| Moldova | 18 | | | | | 1,4 | | | | | 18 |
| Morocco | 28 | 129 | 282 | 829 | 517 | 1,4 | 1,1 | 1 | 0,8 | 0,7 | 1785 |
| Portugal | 32 | 54 | | | | 1,4 | 1,1 | | | | 86 |
| Romania | 146 | | | | | 1,4 | | | | | 146 |
| Serbia | 34 | | | | | 1,4 | | | | | 34 |
| Spain | 167 | 130 | | | | 1,4 | 1,1 | | | | 296 |
| Sweden | 308 | 17 | | | | 1,4 | 1,1 | | | | 325 |
| Syria | 18 | 159 | 252 | 23 | | 1,4 | 1,1 | 1 | 0,8 | | 453 |
| Tunisia | 2 | 29 | 116 | 133 | | 1,4 | 1,1 | 1 | 0,8 | | 280 |
| Turkey | 108 | 37 | | | | 1,4 | 1,1 | | | | 146 |
| Ukraine | 503 | 173 | | | | 1,4 | 1,1 | | | | 676 |
| United Kingdom | 46 | | | | | 1,4 | | | | | 46 |
| Israel | | 8 | | | | | 1,1 | | | | 8 |
| Greece | 2 | | | | | 1,4 | | | | | 2 |
| Norway | 24 | | | | | 1,4 | | | | | 24 |
| Poland | 3 | | | | | 1,4 | | | | | 3 |

SOLAR&WIND 2030 <1.5 €/kg

| | **Total Mton Hydrogen** | | | | | **€/kg Hydrogen per area** | | | | | **Total Mton Hydrogen 2040** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Country | *Area 3* | *Area 4* | *Area 5* | *Area 6* | *Area 7* | *Area 3* | *Area 4* | *Area 5* | *Area 6* | *Area 7* | 493 |
| Algeria | | | | | 3 | | | | | 1,5 | 3 |
| Egypt | | | | | 40 | | | | | 1,5 | 40 |
| Libya | | | | | 26 | | | | | 1,5 | 26 |
| Marocco | | | | | 424 | | | | | 1,5 | 424 |

| Land | km2 for H2 production | Total km2 Land | % of total land used for H2 production | Energy Consumption GWh/yr | Mton H2 production 2040 | Energy from H2 (GWh/yr) | % Electricity consumption supply by H2 |
|---|---|---|---|---|---|---|---|
| Algeria | 1040392 | 2381741 | 44% | 62062 | 5201 | 204938936 | 330216% |
| Belarus | 30993 | 202900 | 15% | 32736 | 122 | 4806553 | 14683% |
| Bulgaria | 4393 | 108612 | 4% | 33134 | 17 | 658582 | 1988% |
| Cyprus | 2223 | 9251 | 24% | 4524 | 9 | 344754 | 7621% |
| Egypt | 319037 | 995450 | 32% | 150579 | 1616 | 63655861 | 42274% |
| Estonia | 17880 | 42388 | 42% | 8858 | 70 | 2772922 | 31304% |
| France | 1095 | 640427 | 0% | 449422 | 4 | 169818 | 38% |
| Hungary | 794 | 89608 | 1% | 41621 | 3 | 123138 | 296% |
| Iraq | 99704 | 437367 | 23% | 43971 | 476 | 18767289 | 42681% |
| Italy | 7927 | 294140 | 3% | 297150 | 31 | 1229360 | 414% |
| Jordan | 23611 | 88802 | 27% | 17384 | 116 | 4573341 | 26308% |
| Latvia | 16525 | 62249 | 27% | 6877 | 65 | 2562782 | 37266% |
| Libya | 893086 | 1759540 | 51% | 25693 | 4514 | 177836764 | 692160% |
| Lithuania | 24724 | 62680 | 39% | 11306 | 97 | 3834324 | 33914% |
| Moldova | 3981 | 32891 | 12% | 5957 | 16 | 617394 | 10364% |
| Morocco | 160905 | 446300 | 36% | 29678 | 850 | 33481551 | 112816% |
| Portugal | 4679 | 91119 | 5% | 48035 | 18 | 725643 | 1511% |
| Romania | 18385 | 231291 | 8% | 55008 | 71 | 2815057 | 5118% |
| Serbia | 3445 | 88246 | 4% | 30292 | 14 | 534268 | 1764% |
| Spain | 24944 | 498980 | 5% | 241563 | 100 | 3922165 | 1624% |
| Sweden | 31370 | 410335 | 8% | 131798 | 121 | 4771539 | 3620% |
| Syria | 45550 | 183630 | 25% | 14263 | 208 | 8211260 | 57570% |
| Tunisia | 17925 | 155360 | 12% | 15838 | 88 | 3471883 | 21921% |
| Turkey | 7149 | 769632 | 1% | 251376 | 28 | 1108704 | 441% |
| Ukraine | 73630 | 579300 | 13% | 128806 | 290 | 11418917 | 8865% |
| United Kingdom | 1402 | 241930 | 1% | 300520 | 6 | 217429 | 72% |

# APPENDIX E HYDROGEN PRODUCTION SOURCES, TECHNOLOGY, MATURITY, AND POSSIBLE RESULT OF HYDROGEN COLOURS

| Source | Process/Technology | Maturity | Colour of Hydrogen |
|---|---|---|---|
| **Natural gas** | Steam methane reforming | Mature | **Grey** or **blue**, |
| | Auto-thermal reforming | Mature | depending on the CCS technology 50-90% of CO2 can be captured and stored. With ATR higher $CO_2$ emission reductions with lower cost are possible |
| | Thermal Pyrolysis | First plant 2025 | **Turquoise**, $CO_2$ emissions<br>Depend on the source for electricity production |
| **Coal** | Partial Oxidation/Gasification | Mature | **Brown** or **blue**, |
| | Underground coal gasification | Projects exist | depending on the CCS technology 50-90% of $CO_2$ can be captured and stored. |
| **Solid Biomass, Biogenic waste** | Gasification | Near Maturity | **Green** |
| | Plasma gasification | First Plant 2023 | Negative $CO_2$ emissions possible |
| **Wet Biomass, Biogenic waste** | Super critical water gasification | First Plant 2023 | **Green** |
| | Microbial Electrolysis Cell | Laboratory | Negative $CO_2$ emissions possible |
| **Electricity + Water** | Electrolysis | | All shades of **grey** to **green** depending on the source for electricity production |
| | Alkaline | Mature | |
| | PEM | Near Maturity | |
| | SOEC | Pilot Plants | |
| **Sunlight + Water** | Photoelectrochemical | Laboratory | **Green** |

# APPENDIX F ERROR MEASUREMENT BETWEEN REAL LAND AREA SIZES AND DATASET LAND AREA SIZES

| COUNTRY | km2 model | km2 real | Error % |
|---|---|---|---|
| Albania | 28654 | 28748 | 100,33% |
| Algeria | 2317510 | 2381741 | 102,77% |
| Andorra | 507 | 468 | 92,31% |
| Austria | 83946 | 83858 | 99,90% |
| Belarus | 207721 | 207600 | 99,94% |
| Belgium | 30652 | 30510 | 99,54% |
| Bosnia and Herzegovina | 51527 | 51129 | 99,23% |
| Bulgaria | 111023 | 110994 | 99,97% |
| Cabo Verde | 4031 | 4033 | 100,05% |
| Croatia | 55889 | 56594 | 101,26% |
| Cyprus | 9137 | 5896 | 64,53% |
| Czech Republic | 78755 | 78866 | 100,14% |
| Faroe Islands | 1484 | 1399 | 94,27% |
| Denmark | 42711 | 44493 | 104,17% |
| Egypt | 998412 | 1001449 | 100,30% |
| Estonia | 45933 | 45339 | 98,71% |
| Finland | 335281 | 338145 | 100,85% |
| France | 548055 | 551695 | 100,66% |
| Georgia | 69957 | 2428 | 3,47% |
| Germany | 357221 | 357386 | 100,05% |
| Greece | 130066 | 131940 | 101,44% |
| Hungary | 92995 | 93030 | 100,04% |
| Iceland | 102952 | 102775 | 99,83% |
| Iraq | 436272 | 438317 | 100,47% |
| Ireland | 69637 | 70273 | 100,91% |
| Israel | 20720 | 21937 | 105,87% |
| Italy | 300077 | 301338 | 100,42% |
| Jordan | 89215 | 89342 | 100,14% |
| Latvia | 64643 | 64589 | 99,92% |
| Lebanon | 10214 | 10400 | 101,82% |
| Libya | 1617580 | 1759540 | 108,78% |
| Liechtenstein | 176 | 160 | 90,91% |
| Lithuania | 65011 | 65300 | 100,44% |
| Luxembourg | 2581 | 2586 | 100,19% |
| Malta | 294 | 316 | 107,48% |
| Moldova | 33688 | 33846 | 100,47% |
| Monaco | 9 | 2 | 22,22% |
| Montenegro | 13797 | 13812 | 100,11% |
| Morocco | 672228 | 446550 | 66,43% |
| Netherlands | 34950 | 41198 | 117,88% |
| North Macedonia | 25463 | 25713 | 100,98% |
| Svalbard | 62905 | 61022 | 97,01% |
| Bouvet Island | 57 | 49 | 85,96% |
| Norway | 320887 | 385178 | 120,04% |
| Palestinian Territory | 6239 | 6020 | 96,49% |
| Poland | 311670 | 312685 | 100,33% |
| Portugal | 91909 | 88416 | 96,20% |
| Romania | 237377 | 238397 | 100,43% |
| San Marino | 60 | 61 | 101,67% |
| Serbia | 88136 | 77453 | 87,88% |
| Slovakia | 48927 | 49036 | 100,22% |
| Slovenia | 20421 | 20273 | 99,28% |
| Spain | 498657 | 498511 | 99,97% |
| Canarias | 7556 | 7493 | 99,17% |
| Sweden | 446025 | 450295 | 100,96% |
| Switzerland | 41489 | 41290 | 99,52% |
| Syria | 188006 | 185180 | 98,50% |
| Tunisia | 155382 | 163610 | 105,30% |
| Turkey | 779988 | 23764 | 3,05% |
| Ukraine | 597504 | 603628 | 101,02% |
| Gibraltar | 8 | 6,8 | 85,00% |
| Guernsey | 73 | 65 | 89,04% |
| Isle of Man | 618 | 57 | 9,22% |
| Jersey | 125 | 120 | 96,00% |
| United Kingdom | 244349 | 242495 | 99,24% |
| Vatican City | 1 | 0,44 | 44,00% |
|  |  | Average | 93,92% |