University of Groningen

Mapping the comparative advantages of potential green and blue hydrogen regions in Europe

Master Thesis

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Abstract

Hydrogen can be used as an energy carrier for renewable energy, which makes it a useful tool for reducing global CO_2 emissions. The Northern Netherlands is one of the European regions that wants to invest heavily into green and blue hydrogen technology. In this master thesis the Northern Netherlands is compared with other European regions that have the same ambition. This is done to evaluate whether the Northern Netherlands is in a good position for establishing a sustainable hydrogen cluster. I have designed a scoreboard to compare eight hydrogen regions on the following five dimensions: natural resources, human capital, transportation & infrastructure, industrial activity and innovation. From this analysis it became clear that the Northern Netherlands is one of the middle performing regions. It excels in the natural resources dimension, due to its high potential for offshore wind. It also has a high score on transportation & infrastructure, because of its dense gas pipeline network and the availability of salt caverns for H_2 or CO_2 storage. One weakness of the Northern Netherlands is its relatively low score on innovation. The Northern Netherlands could especially face tough competition from North Germany and the Schelde-Delta region, because these two regions had good scores across all the dimensions.

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1. Introduction

We currently face a climate crisis that has made it necessary to transition to renewable energy sources. However, currently there is not one single renewable technology that can ensure a reliable energy transition. Each technology has its drawbacks: wind and solar energy fluctuate, this means that there will be times of overproduction and underproduction. This means that in times of underproduction there should be energy from other available sources or there should be previously stored renewable energy available. Hydrogen can be useful for storing this energy because it has a higher storage capacity than batteries. Sustainably produced hydrogen is also required for heavy industry, such as the steel industry and the chemical industry, in order to decrease their CO_2 emissions.

Policy makers and businesses in the Northern Netherlands have ambitions to turn the region into a so-called Hydrogen Valley. The local governments and firms have published a multi-billion euro hydrogen investment plan that gives an overview of the planned hydrogen projects in the region. However, there are more regions in Europe that plan to build a (green/blue) hydrogen cluster. The projects need large investments, and they are associated with both a lot of opportunities and risks. For example, the production of blue or green hydrogen is currently much more expensive than the production of grey hydrogen (Mulder *et al.*, 2019). If carbon pricing policies are not put in place, then it will be unlikely that green or blue hydrogen can be produced at a competitive price.

With these kinds of investments, it is crucial to take the economic geography into account. The aim of this master thesis is to create an overview of the locational advantages and disadvantages of some of the Hydrogen Valleys in Europe, including the Northern Netherlands. This overview is used to evaluate whether the Northern Netherlands is able to compete with these regions in this emerging industry. The research question that is at the core of this master thesis is:

To what degree does the Northern Netherlands have a competitive advantage in green hydrogen production compared to other European hydrogen regions?

This research question will be answered by tackling the following sub questions:
- What factors are necessary for a (green or blue) hydrogen production cluster? (Theory)
- Which regions in Europe aim to build a sustainable hydrogen industry?
- To what degree can the Northern Netherlands compete with other European regions? (Evaluation)

The next chapter explains how hydrogen can be generated and describes the utilities of hydrogen. Chapter 3 will focus on the factors that are needed for creating a green/blue hydrogen cluster by presenting the findings from existing literature. In chapter 4 the European regions that want to invest in green/blue hydrogen are identified. This chapter concludes with the selection of the study regions. Chapter 5 explains the design of the scoreboard and the indicators that will be used to compare the hydrogen regions. Chapter 6 shows the results from the scoreboard and provides an analysis of these results. The conclusion of this master thesis is presented in chapter 7. In this chapter the position of the Northern Netherlands is evaluated based on the results from the previous chapter. This chapter also presents several policy recommendations and suggestions for future research.

2. Hydrogen and its uses

Hydrogen (H2) use today is dominated by industry, namely: oil refining, ammonia production, methanol production and steel production (International Energy Agency, 2019). Currently there is no significant hydrogen production from renewable sources (Mulder *et al.*, 2019; Kakoulaki *et al.*, 2020). Producing hydrogen from fossil fuels is called 'grey' hydrogen, because it also generates CO2 emissions (Figure 1). Currently, the most common method to produce grey hydrogen is with steam methane reforming (SMR), a process by which hydrogen is produced from natural gas (Mulder *et al.*, 2019). The production of hydrogen with natural gas accounts for around three quarters of the annual global (grey) hydrogen production (International Energy Agency, 2019).

A more sustainable alternative is blue hydrogen, which includes the capture and storage of CO2 (CCS) (Kakoulaki *et al.*, 2020). However, CO2-capture efficiencies are only expected to reach a maximum of 85–95%, which means that it is not fully sustainable (ibid). The most sustainable method is to make hydrogen from renewable energy with an electrolyzer, which is called green hydrogen. Electrolysis is a process that splits water into oxygen and hydrogen by bringing the water into contact with electricity (Gasunie, 2019). Electrolysis plants currently have an efficiency of 72% to 80% (Mulder *et al.*, 2019). One of the drawbacks of the green hydrogen production process is that it needs a large amount of electricity. This means that the production of green hydrogen does not seem to be a climate-friendly solution for countries that currently produce a low amount of renewable energy.

At current market prices, hydrogen with carbon capture and storage (CCS) is much cheaper than green hydrogen (Mulder *et al.*, 2019). This means that blue hydrogen could be a good short-term CO2-neutral alternative before making the transition to 100% green hydrogen. It should be kept in mind that the current cost premium for green and blue hydrogen is expected to decrease significantly with further market development and as the volume of deployed hydrogen applications increases (Roland Berger, 2018).

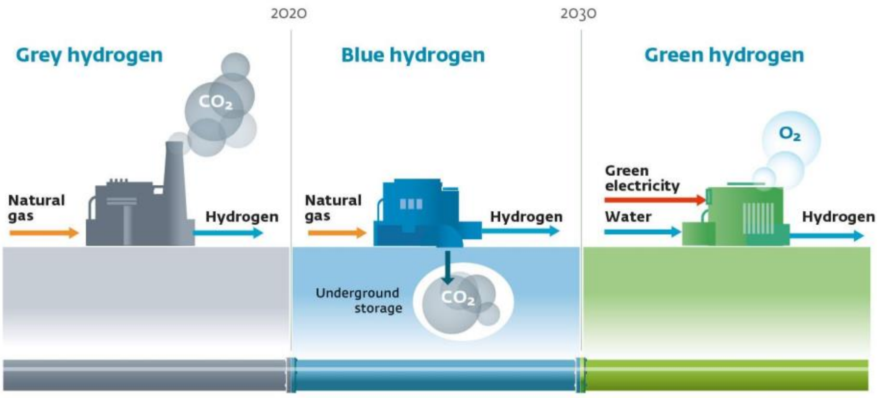


Figure 1: Grey, blue and green hydrogen (Gasunie, 2019)

In this master thesis I focus on the two main methods of hydrogen production: reforming natural gas and capturing the emitted carbon, and electrolysis using renewable energy. Hydrogen can also be produced from coal, nuclear and biomass, but these methods are either less common or more polluting (Ball and Wietschel, 2009).

Hydrogen's uses

Hydrogen is one of the tools that will be used for the energy transition. Hydrogen can be used as an energy carrier, which will enable large-scale renewable energy storage (Roland Berger, 2018). It can help to ensure the security of the energy supply by converting electricity into hydrogen at times when the generation of renewable energy exceeds the demand for electricity (Mulder *et al.*, 2019). This hydrogen can be used to produce electricity again at other times when renewable sources are not able to generate sufficient electricity to meet demand (ibid). Hydrogen can also be used as a sustainable alternative to fossil fuel for long-distance freight transport (Hydrogen Council, 2020). These long-distance transport options currently do not profit from the popularity of electric vehicles, because they have a relatively low range. Hydrogen could also be blended into the existing natural gas network, in order to provide residential and commercial buildings with heat and power (International Energy Agency, 2019). This method is associated with less CO2 emissions than using (pure) natural gas. In addition, hydrogen could be used by (heavy) industry for two goals: industrial energy use and industry feedstock (Roland Berger, 2018; Hydrogen Council, 2020). This means that it can be used to decarbonize the high-temperature processes of energy-intensive industries and the industries that rely on hydrogen as feedstock, such as the production of ammonia and methanol (ibid).

3. Requirements for creating a hydrogen cluster

In this chapter I first discuss the literature regarding industrial clusters. Then, the focus will shift to the factors that are needed to establish a green or blue hydrogen cluster. I also take the locational factors for renewable energy clusters into consideration, because this type of research on green/blue hydrogen clusters is rather scarce. At the end of this chapter, I discuss several separate themes that relate to the locational choice of hydrogen firms in more detail.

3.1 Industrial cluster theory

One of the most important factors in the geography of sustainability transitions is the importance of technological and industrial specialization of a region (Hansen and Coenen, 2015). There has been strong evidence that the formation of new industries is deeply rooted in related activities that have been historically present in a region (Frenken *et al.*, 2007; Neffke *et al.*, 2011). This has led regional policy makers to focus on existing industrial concentrations when they want to stimulate the cleantech industry (Hansen and Coenen, 2015).

Similar to other technologies, the development, demonstration and implementation of green innovations is stimulated by agglomeration economies (Figure 2) such as localized knowledge spillovers, access to a regional specialized pool of engineering qualifications, supporting intermediary organizations and the involvement of universities (McCauley and Stephens, 2012). Specifically for cleantech cluster formation, one of the most important factors is the availability of local natural resources, such as wind and solar power (Hansen and Coenen, 2015).

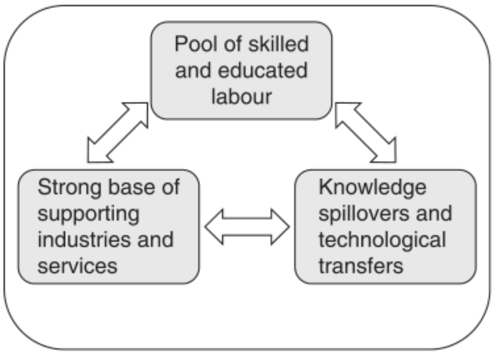


Figure 2: Agglomeration economies (Pike et al., 2016)

Industrial cluster can boost productivity due to proximity to professional human resources and information, complementary relationships between industries and infrastructures, and the competitive pressure (Hidayatno *et al.*, 2019). These agglomeration economies help manufacturers in the cluster to lower their production and transaction costs (Hidayatno *et al.*, 2019). In addition, the intense cooperation and competition within the cluster can lead to new innovations (Hill and Brennan, 2000).

Industrial clusters are also reviewed in research by Porter (2000). He developed the theory of competitive advantage, which includes the following determinants: firm strategy and competitive rivalry, demand conditions, related and supporting industries and factor conditions. (Hill and Brennan, 2000). Figure 3 gives a detailed description of each of these determinants. The factor conditions are the most important element of Porter's theory (Investopedia, 2020). Factor conditions are elements that the region itself can influence, such as a large pool of skilled labor, technological innovation, infrastructure, and capital. The model often also includes two other components: the role of the government and chance (Business-to-you, 2018). The government plays an important role in establishing a good business environment (Hidayatno *et al.*, 2019). In this research I do not take chance into account, because it cannot be influenced. Furthermore, the firm strategy, structure and rivalry are outside of this research's scope, because the focus is on the regional level, which means that it is too complex to look at the individual firms that are located in each region.

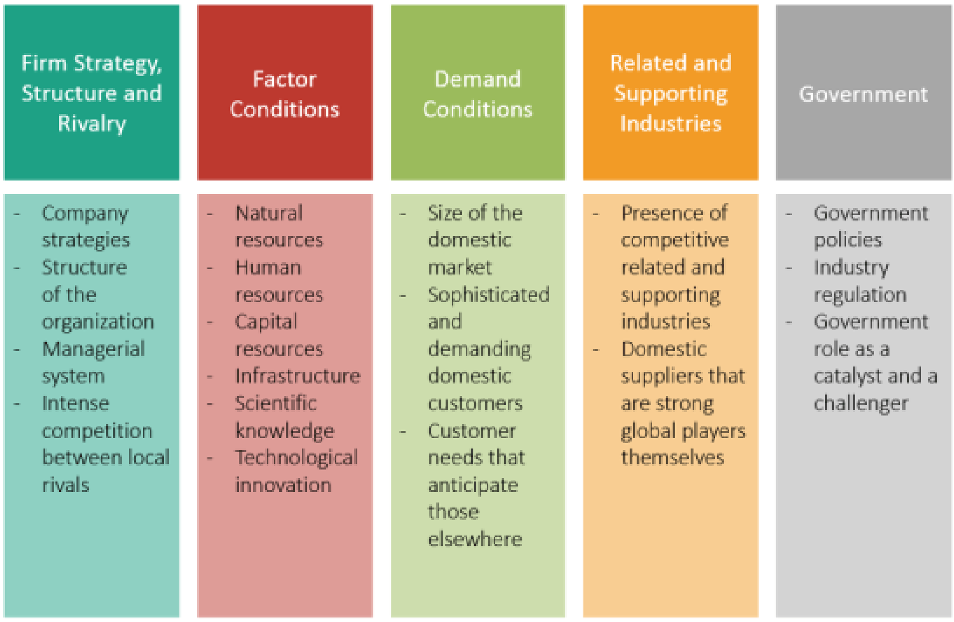


Figure 3: Porter's diamond model (without chance) in detail (Business-to-you, 2018)

When we study the location decision of firms that work with an emerging technology it is also relevant to take the so-called 'technology learning-cycle' into account. Costs and performance tend to improve as technologies pass through different life cycle stages (Rogner, 1998). Initially, costs are high due to low production quantities made by high-skilled workers and low sales volumes and demand. As a technology approaches maturity, labor intensity becomes lower and requires less high-skilled workers, the operation becomes more standardized, mechanized and automated, which leads to lower production costs. When this knowledge is applied to hydrogen, then it is very likely that the emerging green/blue hydrogen clusters will be located in innovative regions, that have high-skilled labor pools.

3.2 Characteristics of renewable energy clusters

One of the most important factors in terms of the location of a hydrogen cluster are the local costs of (renewable) energy production. The cost of hydrogen varies significantly across regions because it depends heavily on the prices and availability of energy inputs. Current hydrogen production occurs mainly in regions with cheaper electricity costs (Caglayan *et al.*, 2021). For the production of blue hydrogen companies require access to low-cost natural gas and large-scale CO2 storage in depleted gas fields or suitable rock formations (Hydrogen Council, 2020). For green hydrogen, the crucial factor is access to low-cost renewables.

Regions that are very active in establishing a hydrogen industry tend to be innovative regions (Madsen and Andersen, 2010). A well-functioning innovation system is crucial for the development of emerging technologies, such as green hydrogen. Less innovative regions should have some other success factors, such as existing hydrogen-production infrastructure if they want to be competitive (ibid). Madsen and Andersen (2010) found a surprisingly weak relationship between the early adoption of hydrogen technology and the existing hydrogen production and pipeline infrastructure in regions. However, they also acknowledge that existing hydrogen production capacities and infrastructure are positive factors for developing hydrogen and fuel cell clusters. This finding means that existing hydrogen infrastructure is not a necessity like low cost (renewable) energy, but it can act as a comparative advantage instead.

The most realistic method for creating a hydrogen cluster is to invest in existing related clusters and to build upon the competences and strengths that are already present in the region (Madsen and Andersen, 2010). Regions that have favorable conditions for hydrogen production are clusters in chemical products, power generation, production technology, oil and gas, and automotive and aerospace technology (ibid). For example, the oxygen that is created during the electrolysis process, could be used by chemical firms in the same cluster (Ministries of Economy and Transport of the North German States, 2019). Another option is to make hydrogen from the waste heat of nearby heavy industry (ibid).

<u>Findings from prior research</u>

Research by He *et al.* (2016) focused on clusters in the wind-power industry. They write that a crucial condition for the success of a wind-power industry cluster is access to highly skilled talent and specialized knowledge related to wind technology. The diffusion of this knowledge and technology can be accomplished by close cooperation between the companies, research institutions and local governments. Etzkowitz and Leydesdorff (1995) also emphasize the importance of interactions between these three actors in the process of innovation. According to He *et al.* (2016), it is also important that supporting companies settle in the cluster, such as suppliers.

Research by Wang *et al.* (2019) found a positive relationship between environmental conditions, the abundance of natural resources and supportive policies with the clustering of renewable energy industries. In contrast, the economic development level and the level of industrialization did not have a significant effect on the development of these renewable energy clusters.

A paper by Fornahl *et al.* (2012) focused on the determinants of the offshore wind energy industry in Northern Germany. They have identified the following factors:

- The available infrastructure, for example the production halls, harbor facilities and heavy lift terminals
- The locally available human capital. Regional competences in firms and workers are available in steel construction (for instance, welding and assembling of large components), maritime logistics and the handling of heavy weight components
- The available deep-water seaports. Waterfront locations along the sea or large rivers are favorable because of the reduced transportation costs
- Policy makers and companies have taken dedicated actions to improve local conditions. One example is the offshore wind energy support policy. This policy consists of R&D and investment support schemes, as well as support for networks and offshore oriented infrastructure
- Research activities, such as the creation of bachelor and master studies about wind energy technology at the local university

According to the Ministries of Economy and Transport of the North German States (2019), favorable regional conditions for creating hydrogen hubs include:

- A concentration of potential users; high regional demand
- A concentration of facilities for renewable electricity generation; to have sufficient renewable electricity for hydrogen electrolysis
- Proximity to seaports; to have the possibility of importing and exporting hydrogen
- Proximity to existing underground storage facilities
- Proximity to electricity and gas transmission networks (pipeline infrastructure)
- Proximity to oxygen consumers

3.3 Education and human capital

Jobs that are specifically related to the production and distribution of hydrogen require mostly high-skilled people, engineering capabilities and technical know-how (FCH JU, 2019). Research by Bezdek (2019) found that jobs in the hydrogen and fuel cell industries are very diverse, and require different types education and training. Many jobs in these sectors require vocational education or on-the-job training, and a university degree is not always required. Occupations in these industries include: scientists, engineers, chemists, managers and technicians (ibid).

The energy transition is expected to mainly create new jobs in installation and construction, according to the Sociaal-Economische Raad (2018). However, renewable energy companies across Europe are finding it difficult to recruit suitably trained employees. The most prevalent skills shortages in this industry are appearing in the construction, installation and the operations and maintenance of these technologies (Blanco and Rodrigues, 2009; Kandpal and Broman, 2014; Lucas *et al.*, 2018; Sociaal-Economische Raad, 2018). The number of engineers that graduate every year seems to be insufficient for the needs of modern economies, which rely heavily upon technological products (Blanco and Rodrigues, 2009). The industry has a high demand for technical worker with practical hands-on training. However, the current focus in renewable energy education appears to be on higher education (Lucas *et al.*, 2018). This means that there is a mismatch between the offered education and the industry demand for qualified technical workers.

Renewable energy education includes vocational level courses that prepare technical personnel for fabrication, installation, operation and maintenance of renewable energy systems (Kandpal and Broman, 2014; Sociaal-Economische Raad, 2018). Furthermore, bachelor and master's degree courses related to renewable energy are required for the design, advice, development and evaluation surrounding the emerging technologies (ibid). Energy is an interdisciplinary subject; programs on renewable energy are offered in the departments of mechanical engineering, chemical engineering, electrical engineering, physics, civil engineering, environmental engineering and architecture (Kandpal and Broman, 2014). However, some academic institutions also offer a separate department for energy that offers programs on renewable energy. There are also master level courses that focus on one specific type of renewable energy, such as hydrogen and fuel cell technology (ibid).

In Europe, the highest share of renewable energy courses is currently being taught at the masters level (>40%), with short-term professional development training following in second place (>30%) (Lucas *et al.*, 2018). Besides university level education, vocational training represents a valuable form of education, with specific emphasis on practical hands-on training. However, less than 10% of the renewable energy courses in Europe fall within this category (ibid). This may suggest that there are currently too many higher education programs being offered that fail to incorporate practical training.

3.4 Transportation and infrastructure

There are a few locational conditions that have to be met for hydrogen production: electrolysis plants need access to the electricity grid and water network (Mulder *et al.*, 2019). For blue hydrogen, it is necessary to locate in proximity to a transport and storage system for CO2, such as empty salt caverns (ibid).

<u>Pipelines</u>

Pipelines have been used to transport hydrogen for more than 50 years, and today, there are about 16.000 km of hydrogen pipelines around the world that supply hydrogen to refineries and chemical plants (Ball and Wietschel, 2009). Dense hydrogen pipeline networks exist for example between Belgium, France and the Netherlands and in the Ruhr area in Germany (ibid). Pipelines are the preferred option for transporting large quantities hydrogen (Ball and Wietschel, 2009; Mulder *et al.*, 2019). Hydrogen can also be transported with trucks or by sea when it is turned into liquid hydrogen or ammonia (NH3). The transport of hydrogen is expensive either way; pipelines have high capital costs and transporting liquid or gaseous hydrogen with trucks is associated with high operational costs (Ball and Wietschel, 2009). This means that it is preferred to produce hydrogen close to centers with high energy demand.

The investments in a hydrogen pipeline are up to two times higher than those for natural gas pipelines, because of hydrogen's specific physical and chemical properties (Ball and Wietschel, 2009). However, existing gas pipeline infrastructure can be enhanced in such a way that they can be used for the transportation of hydrogen (Raad voor de leefomgeving en infrastructuur, 2021). Adapting the existing gas pipelines is considerably cheaper than building new pipelines; repurposing the existing gas infrastructure is expected to be between 10 and 35% of the costs that would be required for a newly built hydrogen pipeline (Gas Infrastructure Europe *et al.*, 2021).

<u>Underground storage of CO2 and hydrogen</u>

There are three major types of underground gas storage options: depleted gas/oil reservoirs, aquifers and salt caverns (Zivar *et al.*, 2020). These types of underground storage are used for different types of gas storage, such as: CO2 storage, methane storage and hydrogen storage. The required structure for CO2 storage is similar to the required storage structure for hydrogen (ibid). CO2 storage is intended to be permanent. This contrasts with hydrogen storage, which is intended to be more short-term and cyclical (ibid). This means that the storage facility for CO2 from blue hydrogen cannot be used for (green) hydrogen in a later stage.

Underground storage of hydrogen in salt caverns is a technically feasible option for large-scale storage of electricity (HyUnder, 2014). Salt caverns are considered to be the most promising option because of their large storage capacity and their low investment costs (Caglayan *et al.*, 2020). For underground hydrogen storage it is preferred to be located near wind resources and also to be in the vicinity of the electric and natural gas grids (Simon *et al.*, 2015). Another factor that can be taken into account is the local hydrogen demand.

Figure 4 shows the distribution of salt formations that can be used for storage across Europe (Crotogino *et al.*, 2010). Salt deposits suitable for cavern construction are unevenly distributed geographically (HyUnder, 2014). The most favorable geological conditions for gas storage caverns exist in the northwest of Germany and the northeast of the Netherlands (Crotogino *et al.*, 2010; HyUnder, 2014). In contrast, regions in southern Germany or central France lack either salt formations completely or have unsuitable salt deposits (Crotogino *et al.*, 2010).

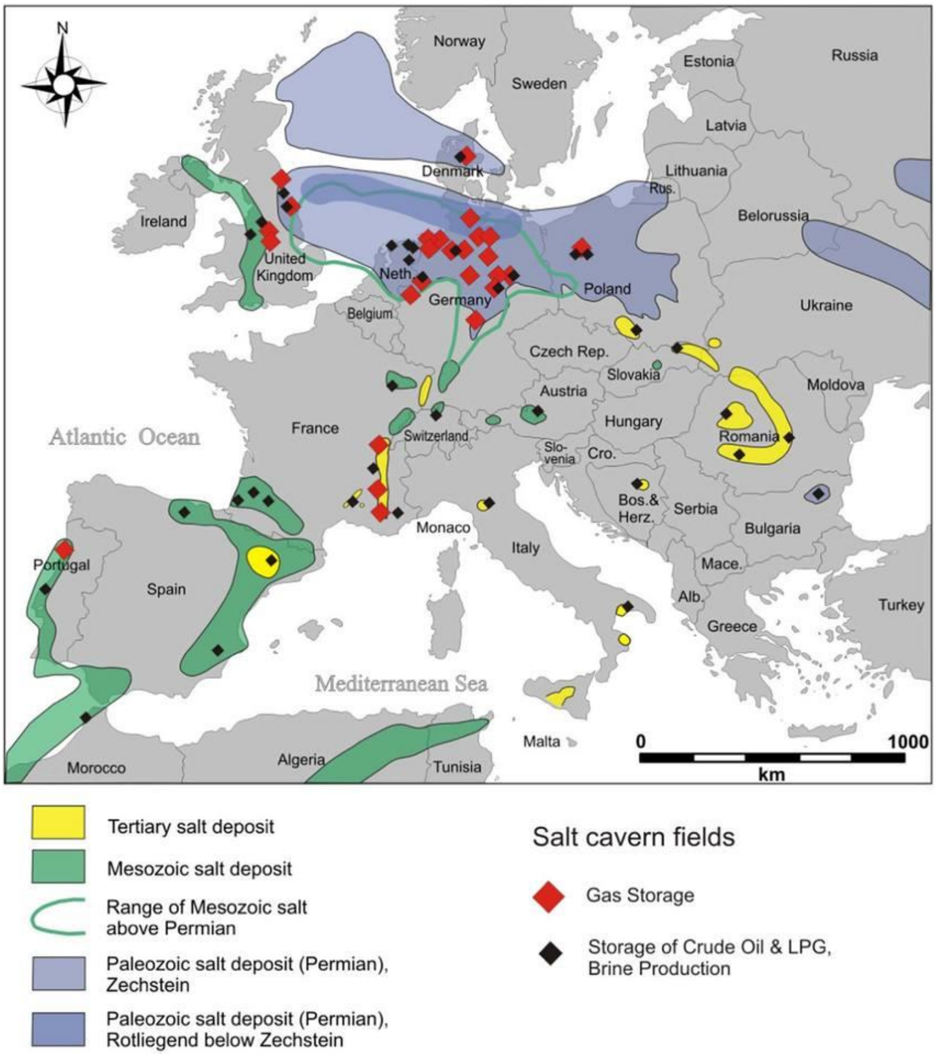


Figure 4: Salt caverns in Europe (Blanco and Faaij, 2018)

<u>Seaports</u>

Seaports that are located in the Hydrogen Valleys can function as logistics hubs for importing and exporting green hydrogen (Ministries of Economy and Transport of the North German States, 2019). One example would be to import hydrogen from regions with favorable conditions for solar or wind power, such as North-Africa or the Middle-East (Mulder *et al.*, 2019).

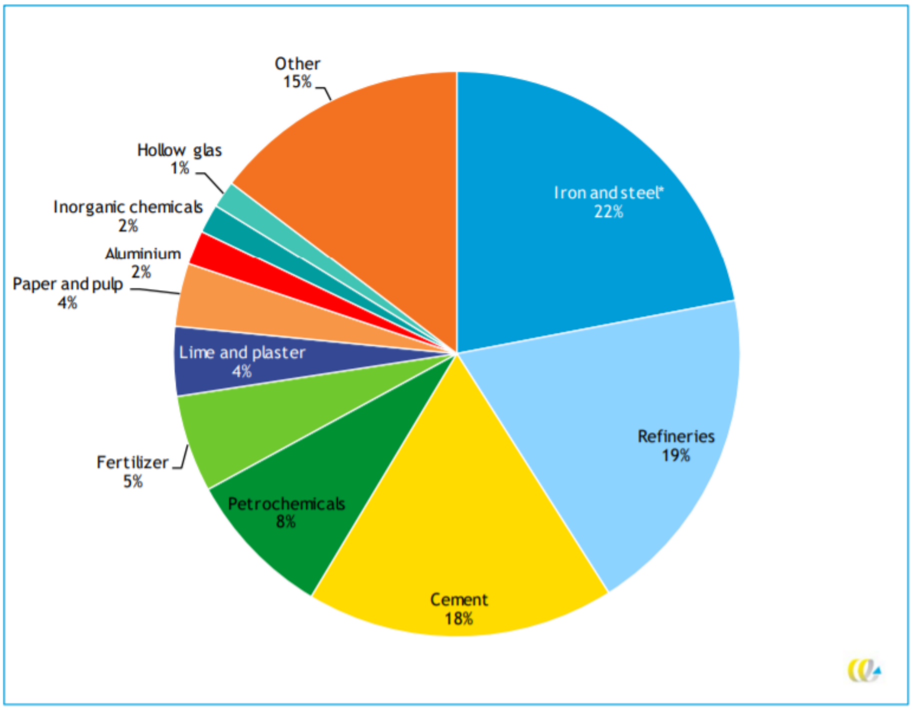
In addition, the existing liquefied natural gas (LNG) terminals that are present at some European ports can be adapted for the import/export and storage of hydrogen (European Commission, 2020a; Gas Infrastructure Europe *et al.*, 2021).

3.5 Industrial activity

Energy-intensive industries

The following industries are considered to be energy-intensive: food, pulp and paper, basic chemicals, refining, iron and steel, nonferrous metals (primarily aluminum), and nonmetallic minerals (primarily cement) (U.S. Energy Information Administration, 2016). Together, they account for about half of all industrial sector delivered energy use. In 2012, energy-intensive industries accounted for about 54% of the OECD's total industrial sector energy consumption.

In 2012, the three largest industrial energy consumers in the OECD were: the basic chemicals industry, with 19% of the total industrial energy consumption, the iron and steel industries (10%) and the refining industry (8%) (U.S. Energy Information Administration, 2016). In addition, the same industries emit large quantities of carbon dioxide (CO2). Figure 5 shows the emissions of industrial sectors in the EU. This figure shows that the iron and steel sector has the greatest share of emissions followed by refineries, cement, petrochemicals and fertilizer (de Bruyn *et al.*, 2020). Together these five sectors make up over 70% of industrial emissions in the EU. In addition, half of all the emissions in the energy-intensive industries are being caused by heating fossil fuels in furnaces for high-temperature processes. Industrial heating is mainly used in the following industries: iron and steel, refineries, chemicals and non-metallic minerals (includes cement) (ibid).



Source: EUTL, calculations CE Delft

Notes: * Emissions of the iron and steel sector exclude emissions from burning waste gasses to generate electricity

Figure 5: Share of CO2 emissions per industry in the EU in 2018 (de Bruyn et al., 2020)

In summary, the three largest energy producers in the OECD are the chemical industry, the iron and steel industry and the refining industry. These same industries in addition to the cement industry account for the largest share of industrial CO2 emissions in the EU.

3.6 Conclusion

Porter's diamond model offers four dimensions that can be used for analyzing a region's comparative advantage. This model shows overlap with the benefits of agglomeration, which include: increased knowledge spillovers, access to a skilled and educated labor pool and access to supporting industries (Pike *et al.*, 2016). The categories of the diamond model that will be used for this research are: factor conditions, demand conditions, related and supporting industries and the regional government.

The factor conditions that will be analyzed in this research are: natural resources, human capital, infrastructure and innovation. Low electricity costs are the most important factor for hydrogen production in terms of natural resources. For green hydrogen production there needs to be an abundance of solar and wind, and for blue hydrogen there needs to be a large amount of natural gas with CO2 storage options, such as depleted gas/oil reservoirs or salt caverns. Furthermore, a successful hydrogen cluster needs a large labor pool with high-skilled people, engineers and technical personnel. Jobs related to hydrogen require different types of education and training; they require both vocational and tertiary education. It is also recommended that universities in the region provide courses regarding hydrogen technology. In terms of infrastructure, it is beneficial for a hydrogen producing region to have access to one or multiple seaports for the import/export of hydrogen. Finally, green and blue hydrogen production is an emerging technology, which means that more innovative regions are in a better position to establish a cluster for the sustainable production of hydrogen.

The demand conditions can be interpreted as the regional demand for hydrogen. For example, by the heavy industry in the region. There are multiple examples of related and supporting industries for hydrogen. One example would be the natural gas industry, because their gas pipelines can be adapted for the transportation of hydrogen. Another strategy is to locate the hydrogen production process close to a cluster of chemical firms and other consumers of hydrogen. Lastly, the regional government is relevant because they can put policies in place that support the establishment and growth of a hydrogen cluster in their region. This conclusion will act as the starting point for the design of the scoreboard, which will be discussed in the methodology chapter.

4. Planned hydrogen clusters in Europe

In this chapter the objective is to identify the NUTS 1 and NUTS 2 regions in Europe that will be used for the analysis. First, the planned hydrogen clusters in Europe will be introduced. After that, the process will start of selecting an appropriate amount (10 to 15) of regions that will be analyzed during this research. This selection will be based on the size of the hydrogen investment plans for each region. In this research I solely focus on Europe, because European countries will require a large amount of hydrogen produced from renewable sources in order to decarbonize their economies. Importing hydrogen from regions like North-Africa or the Middle-East is not (yet) feasible, because this is associated with high transport costs (Mulder *et al.*, 2019).

<u>Hydrogen Valleys</u>
The indicated investments in hydrogen and fuel cell technology are well spread across Europe. Regions with ambitions to become Hydrogen Valleys are mainly located in countries which already have substantial experience in hydrogen and fuel cell activities, in particular the UK, Belgium, the Netherlands, Germany and France (Roland Berger, 2018). The largest share of investments will be realized in Central Europe, especially in Germany (Roland Berger, 2018). Very high planned investments in two regions in this country account for about 40% of the total indicated investment volume (ibid).

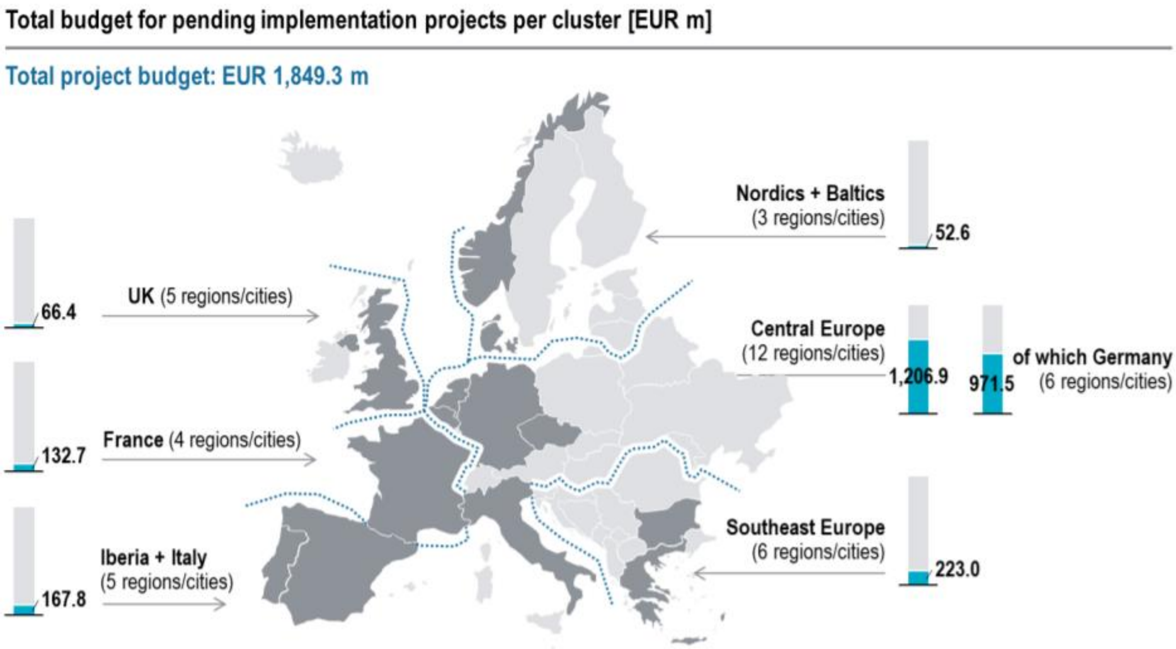


Figure 6: Planned investments across European regions (Roland Berger, 2018)

The Northern Netherlands Hydrogen Investment Plan 2020 contains a map that shows global hydrogen hubs. They have identified the following European regions (New Energy Coalition *et al.*, 2020): Scotland (UK), Geirangerfjord (NO), Aragon (ES), Auvergne-Rhône-Alpes (FR), Bolzano (IT), Copenhagen (DK) and Hamburg (DE). In addition, the EU's Smart Specialisation (S3) Platform identifies four leading regions in the emerging hydrogen industry (European Commission, 2020b): Auvergne-Rhône-Alpes (FR), Aragón (ES), Northern Netherlands (NL) and Normandy (FR).

Table 1: Hydrogen regions according to two different sources

	Northern Netherlands Investment Plan	S3 Leading regions
North Netherlands (NL)	x	x
Aragon (ES)	x	x
Auvergne-Rhône-Alpes (FR)	x	x
Normandy (FR)		x
Scotland (UK)	x	
Geirangerfjord (NO)	x	
Bolzano/Bozen* (IT)	x	
Copenhagen (DK)	x	
Hamburg (DE)	x	

*Bolzano/Bozen is also known as South Tyrol.

<u>Region selection</u>

The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) have identified 21 Hydrogen Valleys in Europe (FCH JU, 2020). Their platform provides insights into project development of the most advanced Hydrogen Valleys around the globe (ibid). Hydrogen Valleys are regions and cities that pursue very ambitious plans to realize large-scale hydrogen and fuel cell activities (Roland Berger, 2018). This group of Hydrogen Valleys is very heterogeneous in terms of existing levels of experience and the status of the implementation of their plans. However, they have typically secured broad stakeholder support for the development of their projects (ibid). FCH JU's dataset with Hydrogen Valleys is based on concrete projects. For example, it only shows the HEAVENN project for the Northern Netherlands, which has an investment volume of 88 million euros. Even though, the investments in the Northern Netherlands investment plan amount to over 9 billion euros (New Energy Coalition *et al.*, 2020). We can distinguish roughly three types of projects from the Hydrogen Valley dataset:

- Fully implemented, relatively small pilot projects, such as HyBalance in Hobro in Denmark (€ 15 M) and BIG HIT on the Orkney Islands in Scotland (€ 13,5 M)
- Concrete projects of a larger scale like HEAVENN in the Northern Netherlands (€ 88 M) and Zero Emission Valley in France's Auvergne-Rhône-Alpes (€ 70 M)
- More abstract government plans with an even bigger scope, such as HyNet North West in the UK (€ 4000 M) and NDRL in Northern Germany (€ 325 M)

5 of the 21 Hydrogen Valleys are transnational EU projects, such as the Green Octopus project which spans 5 EU countries. These projects all have high investment volumes (between € 1,5 billion and € 9,7 billion), but the projects are not yet in the implementation phase. These projects are spread across multiple regions, and it is not yet known how the investments will be spent across each region. This makes these projects unfit for my research design; these 5 projects will not be included in this research. The WIVA P&G project (€ 79 M) in Austria is also excluded, because their planned hydrogen projects are spread across the entire country. This means that I will not include this project in the regional analysis.

The regions are compared on the NUTS 1 and NUTS 2 spatial scale, due to data availability. This means that the three Hydrogen Valleys in Germany that are based on a metropolitan region are excluded. One of these projects, namely the HyWays for Future project (€ 90 M) in the Metropolitan region of Bremen/Oldenburg, lies within Northern Germany. This means that this project will be analyzed indirectly, when the NDRL project is analyzed.

In this research I exclude the four smallest projects, which have an investment volume of less than 40 million euros. For France, the two S3 leading regions are picked, which means that the Hydrogen Valley in the Bourgogne-Franche-Comté region did not make the final selection. This is done in order to get a diverse set of regions across different European countries.

It is important to mention that there are also investment plans regarding hydrogen in Rotterdam. One example is the H-vision project which is made up of a 2 billion investment plan (Laat, 2020). However, Rotterdam was not included in the list with Hydrogen Valleys at the start of this research. The investment plans in Rotterdam also do not seem to have a regional perspective; the projects mainly focus on the city of Rotterdam itself. However, it should be noted that two Dutch Hydrogen Valleys were added to FCH JU's Hydrogen Valley platform after this research was conducted: one in Amsterdam and one in Rotterdam. Furthermore, the region of Aragon in Spain does not appear among the Hydrogen Valleys; it is the only S3 leading region that is not present in the list of Hydrogen Valleys. I still choose to include this region in the analysis, because it is both one of the S3 leading regions and it is identified as a competitor in the Northern Netherlands investment plan. Table 2 shows the selection of regions that will be analyzed.

Table 2: Overview of the hydrogen regions that are analyzed

Project / Developer	Country	Region	NUTS	Investment (€ M)	H2 production (T/day)	Status
HEAVENN / New Energy Coalition	NL	North Netherlands	NUTS 1	88	7,7	Start of implementation
Hydrogen Delta / Smart Delta Resources	NL / BE	Zeeland (NL) East Flanders (BE)	NUTS 2 NUTS 2	>100	140	Concrete project plan
Living Lab Northern Germany	DE	Bremen Hamburg Mecklenburg-Vorpommern Lower Saxony Schleswig-Holstein	NUTS 1/2 NUTS 1/2 NUTS 1/2 NUTS 1 NUTS 1/2	325	10	Concrete project plan
Zero Emission Valley	FR	Auvergne-Rhône-Alpes	NUTS 1	70	1,6	Start of implementation
Normandy Hydrogen	FR	Normandy	NUTS 1	N.A.	N.A.	Start of implementation
HyNet North West / Progressive Energy	UK	North West England	NUTS 1	4.000	2.160	Concrete project plan
Hydrogen Valley South Tyrol / Institute for Innovative Technologies (IIT)	IT	Autonomous Province of Bolzano/Bozen	NUTS 2	55	1	Start of implementation
Hydrogen Master Plan in Aragon 2016-2020	ES	Aragon	NUTS 2	N.A.	N.A.	N.A.

These 8 Hydrogen Valleys are located in the following 7 countries: the Netherlands, Belgium, Germany, France, the United Kingdom, Italy and Spain. The 8 valleys consist of 5 NUTS 1 regions, 4 NUTS 1/2 regions and 4 NUTS 2 regions. Figure 7 shows the location of these regions. The German states of Bremen, Hamburg, Mecklenburg-Vorpommern and Schleswig-Holstein can be considered both as

NUTS 1 and NUTS 2 regions. The provinces of Zeeland and East Flanders are jointly called the Schelde-Delta.

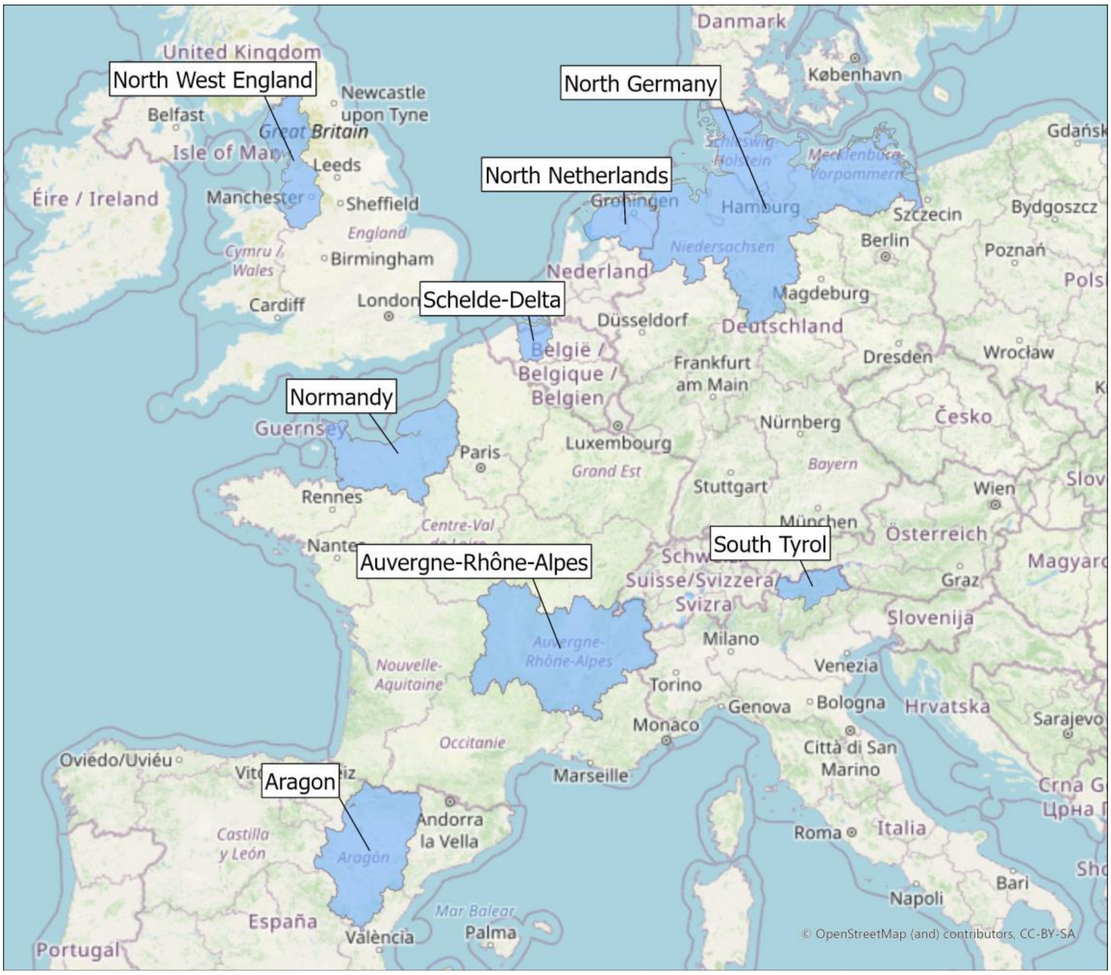


Figure 7: Study regions

5. Methodology

In the previous chapter, I have chosen the regions that will be used for the comparative analysis. This chapter describes the research methods that will be used to create a framework that will be used to compare each region's characteristics. This scoreboard includes multiple factors that should give a clear overview of the strengths and weaknesses of each region regarding their hydrogen production potential. The research is based on existing literature and data.

5.1 The design of the scoreboard

The methodology for this research is inspired by the OECD's regional well-being framework. The OECD framework for regional well-being measures well-being with a multi-dimensional approach (OECD, 2018). They have identified eleven dimensions that play a key role in individuals' well-being and provide a set of indicators to measure them, to allow for comparisons between the regions. They do not make a single statement about the overall well-being in a region. Instead, they present the information in such a way that users can consider the relative importance of each dimension (ibid). For each dimension, a score on a scale from 0 to 10 is attributed to the region, based on one or more indicators. A higher score indicates better performance in a topic relative to all the other regions. Figure 8 shows an example of this framework.

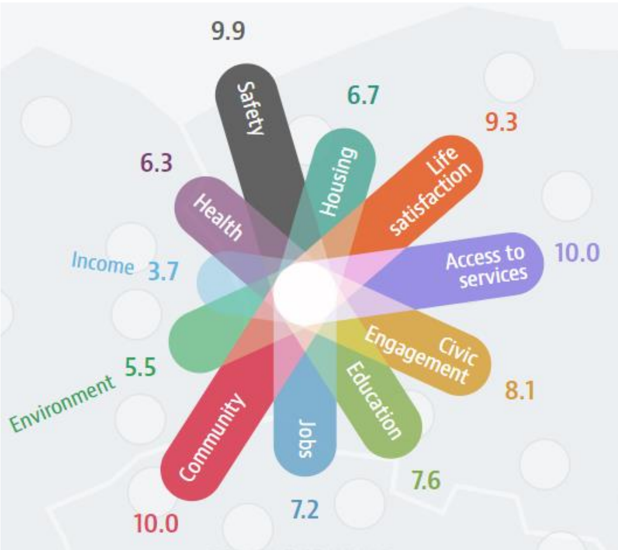


Figure 8: Groningen's regional wellbeing (OECD, 2018)

The choice for a scoreboard is a compromise between a large list of indicators and an all-inclusive (composite) index. There is a tradeoff between a composite index on the one side and a wide range of indicators on the other side. A composite index gives a single unified view, but it may dilute information (OECD, 2018). A wide range of indicators offers detailed information but is much more difficult to interpret and communicate (ibid). A composite index would not be suitable for the complexity and broadness of this situation. In addition, it would be too complicated to calculate, and it could be more sensitive to possible biases. Presenting a large list of indicators is also not an option, because this would make it too cumbersome to compare regions. The scoreboard consists of 5 dimensions with each one or multiple indicators. The scores on the indicators are weighted and lead to a score on each dimension. The scores on the dimensions can then be used to compare regions. Table 3 shows the content of the scoreboard.

Table 3: Content of the scoreboard

Dimension	Indicator	Weight
Natural resources	- Green electricity potential	75%
	- Amount of electricity generated from natural gas (blue H2)	25%
Human capital	- Share of people working in electricity, gas, engineering etc.	40%
	- Share of employees in science and technology	25%
	- Share of vocationally or tertiary trained people	35%
Transportation & infrastructure	- Existing gas pipeline infrastructure	40%
	- CO2/H2 storage potential	35%
	- Access to a port	25%
Industrial activity	- Share of industrial activities in the total GVA	25%
	- Total electricity consumption	25%
	- Employment share of heavy industries	50%
Innovation	- Number of patent applications	50%
	- Public and private R&D expenditures	50%

The dimensions and their indicators are based on Porter's diamond model, earlier research about renewable energy clusters, and on strategy documents that were written about the study regions. Four dimensions are based on the factor conditions from Porter's diamond model. These are: natural resources, human capital, transportation & infrastructure and innovation. The demand conditions and the related and supporting industries in Porter's diamond model are combined in the industrial activity dimension. This was done because hydrogen consumers mostly consist of industrial firms that operate in related sectors. The degree of support from regional institutions is not included in the analysis, because it is rather difficult to measure due to its qualitative nature. Also, regional policies or plans regarding hydrogen are not readily available on the internet for every region. Appendix A shows summaries of the information that was found about each of the individual Hydrogen Valleys. This information was retrieved from multiple online sources.

A wide range of variables will be used, including dummies (pass/fail) and ratio variables. I use the versatile 1-5 scale, because it is able to fit dummies as well as ratio variables; it makes the dummies more detailed and the ratio variables less detailed. For ordinal and dummy variables, I use the 1-5 scale to rate the regions from very bad (1) to very good (5). The ratings of ratio variables are calculated with two formulas that are combined later on. There generally is a small and nuanced difference between the outcomes of both formulas. I use two formulas, because it makes the calculation of the final ratings more transparent and robust. The first formula is the min-max method, which determines the position of a value based on the minimum and the maximum values for that indicator (OECD, 2018). This formula is very precise. However, it relies heavily on the minimum and maximum values, which makes it vulnerable to outliers. The formula for this first score is:

$$\frac{x - Min}{Max - Min}$$

Each region's value (x) is compared with the region with the lowest value (Min) and the region that has the highest value (Max) for that indicator.

The other formula is Microsoft Excel's percent rank function. This function ranks the regions in a proportional manner, which decreases the influence of outliers. The drawback of this function is that it does not take the size of the differences between each value into account; it simply ranks the values. These two scores are then used to calculate the score on the 1-5 scale. For this I take the mean of both scores and multiply this with 4 and add 1, to convert the score to the 1-5 scale. The lowest value will get a score of 1,0 and the highest value will have a score of 5,0. The final score of a dimension will be calculated based on the scores of the indicators and their weights. The weights are based on the author's estimation of the importance of each indicator.

ArcGIS Pro was used for spatial analysis. Microsoft Excel was used for working with the scoreboard data and for the calculation of the ratings.

5.2 Methods per indicator

Natural resources

Data on existing production of renewable energy was not available for this spatial scale. For that reason, I will be using the potential for green electricity also as a proxy for the existing production of renewable energy. However, it should be emphasized that a high potential for green electricity is only a comparative advantage when the regional policy makers also use this potential by placing solar panels or/and building wind turbines. Data on the technical potential for green electricity of NUTS 2 regions in Europe was retrieved from a paper by Kakoulaki *et al.* (2020). They have estimated the technical potential for electricity generation from wind and solar and the existing hydropower resources for NUTS 2 regions in Europe. The potential for green electricity is divided by each region's area, because that makes it possible to compare NUTS 1 and NUTS 2 regions. In addition, there are large size differences within the same spatial scale. For example, Auvergne-Rhône-Alpes and Bremen are both NUTS 1 regions, but the former has a size of 71.134km2 compared to the latter which has a size of only 420km2 (Eurostat, 2021b).

For the production of blue hydrogen, I take the amount of electricity generated from natural gas in each region into account. Regional data on natural gas production was not available, and that is why this proxy instead. Here it is assumed that regions that produce a large amount of natural gas are expected to have a higher amount of electricity generation from natural gas. Natural gas is the only fossil fuel that will be included in this analysis because it is the most common method of producing hydrogen currently. In addition, regional data on energy production with coal was unavailable. The Netherlands and the UK are the second and third largest producers of natural gas in Europe behind Norway, with both having a production of more than 40 billion m3 in 2017 (The World Factbook, 2017). Germany and Italy also had a sizeable production in the same year of 7,9 billion m3 and 5,55 billion m3, respectively. Spain, France and Belgium all had less than 40 million m3 in 2017.

Figure 9 shows the regional distribution of the estimated amount of electricity generated from natural gas in European NUTS 2 regions. From these two maps it becomes clear that the amount of electricity that is generated with natural gas will decline sharply in the next decade. The Northern Netherlands currently has the highest amount of electricity generation from natural gas out of all the Hydrogen Valleys; the province of Groningen has generated more than 20 petajoule (PJ) in 2020. It is however important to note that the production of natural gas in Groningen will decrease sharply in the coming years, due to the local earthquakes and their social impact. It is expected that the production of natural gas will diminish to zero in the year 2022 (De Rijksoverheid, 2021). The region of Zeeland, which belong to the Schelde-Delta, is expected to generate between 10 and 20 PJ of electricity from natural gas in 2020. Northern Germany contains two NUTS 2 regions with at least 5 PJ of electricity from natural gas. North West UK also has one region with at least 5 PJ in 2020. The remaining Hydrogen Valleys do not have a significant amount of electricity generated from natural gas. This information was retrieved from a report by the Joint Research Centre (2016). In this report they have forecasted the generation of electricity from natural gas for European NUTS 2 regions in 2020 and 2030 based on prior data.

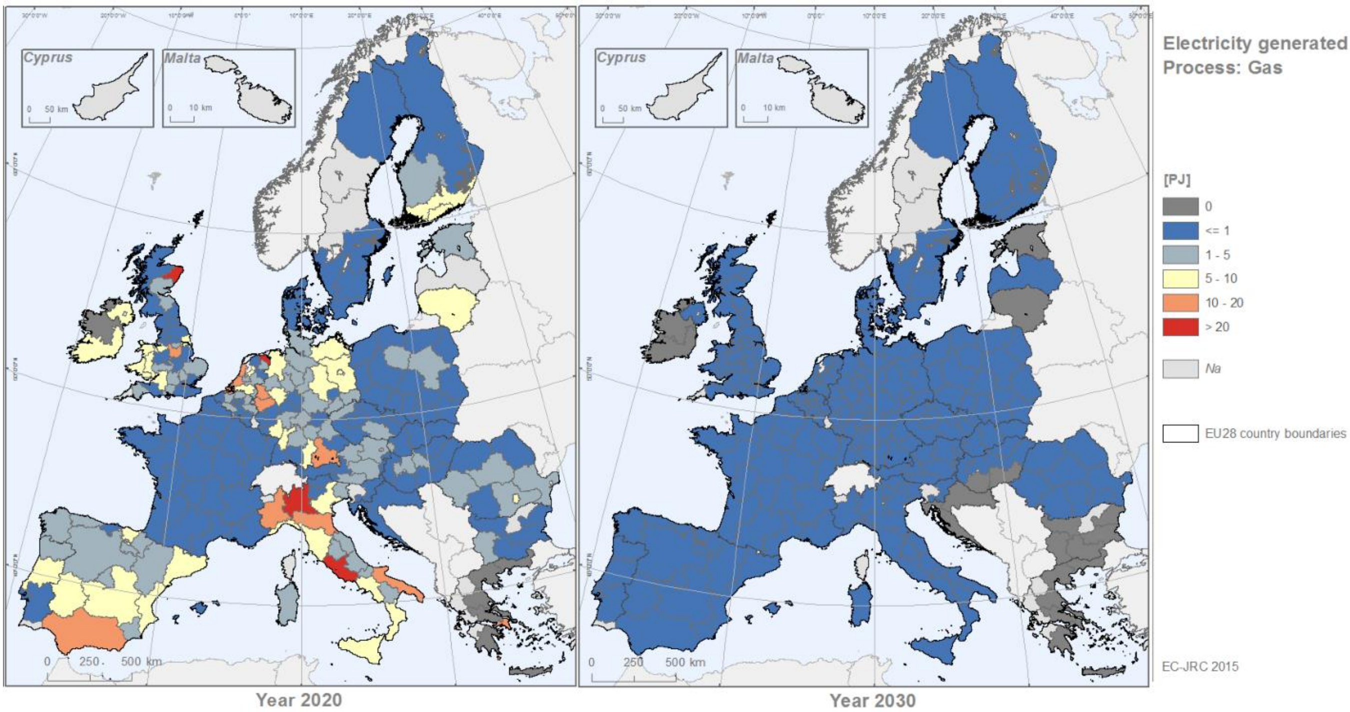


Figure 9: Forecast of electricity generation from natural gas in NUTS 2 regions in 2020 and 2030 (Joint Research Centre, 2016)

The potential for green electricity has a higher weight than the natural gas indicator because the production of renewable energy is much larger than the production of natural gas in Europe. In 2018, more than 80% of all natural gas usage in Europe was covered by imports, with Russia being the largest natural gas supplier (Eurostat, 2021a). This means that most future European hydrogen clusters will probably be based on hydrogen production from renewable energy. Also, the production of renewable energy in Europe has increased by 49,2% between 2008 and 2018, while the production of natural gas has decreased by 46,4% in that same time period (ibid). This trend in favor of renewable energy is expected to continue, due to the EU's climate targets.

Human capital

Human resources in science and technology consists of two groups: the ‘professionals’ group, which includes scientists, engineers and other professionals, and the ‘technicians and associate professionals’ group (Eurostat, 2020). In 2019, 54,4 % of the employees in science and technology (aged between 25 and 64) were 'professionals' and 45,6 % were ‘technicians’ in the EU-27. However, the proportions differed greatly between EU member states (ibid). This indicator gives insight in the proportion of high-skilled workers in each hydrogen region. It also shows the proportion of technicians in each region, which is also relevant for establishing a hydrogen cluster. This indicator has a lower weight than the other two indicators, because this indicator is expected to bias the result towards the more highly educated group of workers. This means that a lower weight for this indicator will give a more balanced view of the labour pool by taking both the vocational and tertiary educated workers into account.

Educational attainment data is for the age group 25 to 34 years, because the data for 25 to 64 years was unavailable on Eurostat. The 25 to 34 years age group gives a good overview of both current education levels and the expected future education levels. The percentage of the population that completed vocational education and the group that completed tertiary education are combined, because a high percentage of people that completed tertiary education often leads to a low percentage for the group that completed vocational education. I consider both of these groups to be suitable for working in the renewable energy industry and will thus not make a distinction between the two.
The share of the employment in the electricity, gas, steam, air conditioning, water and construction sectors is used to get insight into each region’s labor pool. I consider the electricity, gas, steam and air conditioning supply sectors closely related to the hydrogen sector. Workers that work in related fields are expected to face less friction when transferring to the hydrogen sector. The employment in the electricity, gas, steam and air conditioning supply sectors has too many missing values. Instead, I use the broader employment category that also includes construction and water from Eurostat (2021b). This still gives a good insight in the employment in related sectors, because it can be argued that the construction and water sectors are also related to hydrogen to a certain degree.

The human capital dimension was also supposed to include an indicator on the availability of study programs relating to renewable energy. However, from the information on the internet it becomes clear that the universities in these hydrogen regions all offer courses on renewable energy or environmental engineering, except for South Tyrol. Table 4 shows some examples of study programs relating to renewable energy for each of the regions. The university in South Tyrol offers a course in energy engineering, which also prepares students for working with renewable technology (Free University of Bozen-Bolzano, 2021). This means that this indicator will not be used for the scoreboard; all the regions offer specific programs for students that want to work with renewable energy.

Table 4: Examples of renewable energy studies in the Hydrogen Valleys

Region	University	Programme	Level	Source
North Germany	Hamburg University of Applied Sciences	Renewable Energy Systems - Environmental and Process Engineering	MSc	study.eu
Aragon	School of Engineering and Architecture - Zaragoza	Renewable Energies and Energy Efficiency	MSc	estudios.unizar.es
North West (UK)	The University of Manchester	Renewable Energy and Clean Technology	MSc	manchester.ac.uk
Normandy	Université Le Havre Normandie	Renewable Energy & Civil Engineering	2nd year Master	univ-lehavre.fr
Auvergne-Rhône-Alpes	INSA Lyon	Energy and Environmental Engineering	MSc	insa-lyon.fr
North Netherlands	Hanze University of Applied Sciences – Groningen University of Groningen	European Master in Renewable Energy Energy and Environmental Sciences	MSc MSc	studyportals.com rug.nl
Schelde-Delta	Ghent University	Environmental Technology and Engineering	MSc	studiekiezer.ugent.be
South Tyrol	Free University of Bozen-Bolzano	Energy Engineering	MSc	unibz.it

<u>Transportation and infrastructure</u>
The SciGRID_gas project provides an open-source gas transmission data model for Europe (Diettrich *et al.*, 2021). They have converted a PDF map by EntsoG, which shows all the gas pipelines in Europe, into GIS data. EntsoG is the acronym for 'European Network of Transmission System Operators for Gas' and is an association of the European transmission system operators (ibid). They used the latest version of this map, which is from 2019. I have used the intersect tool to determine which pipelines lie with each region. The length of the sections of each pipeline that are located within a region were summed to determine the total length of the gas pipelines for each region. This was divided by the region's area, get a good indicator for the concentration of gas pipelines for each region. Existing gas pipelines can be repurposed for hydrogen use. This means that a region is more suitable for establishing a hydrogen cluster when it has more existing gas pipelines. However, it is important to note that there are different types of gas pipelines for different purposes. For example, gas pipelines that are used for residential power and heat will only be useful for hydrogen use, when the hydrogen (blended with natural gas) is used for the exact same purpose. Still, for this master thesis it will be too complex to take the different types of gas pipelines into account.

Ports can be used for the import or export of hydrogen. 5 of the 8 study regions have multiple ports and direct access to the sea. From geodata on the location of ports in Europe by Eurostat (2014), it becomes clear that there is also one port in the landlocked region of Auvergne-Rhône-Alpes; the port in Lyon. By using Google Maps, it has become clear that these 6 regions all have hydrocarbon terminals, which means that they already have energy related knowledge and facilities. However, none of the regions has an LNG terminal (Gas Infrastructure Europe, 2019). Yet, there are plans in North Germany to construct two LNG terminals that could be operational in 2022 (ibid).

To determine whether a region has hydrogen or CO2 storage potential, I used a map by Gas Infrastructure Europe (2018) that shows salt caverns and depleted gas fields in Europe. The most favorable geological conditions for gas storage caverns exist in the northwest of Germany and the northeast of the Netherlands (Crotogino *et al.*, 2010). In addition, there are salt caverns in Cheshire (North West UK) and in Auvergne-Rhône-Alpes (Etrez, Tersanne and Hauterive). Also, Serrablo in Aragon has a depleted gas field.

I consider the existing pipeline network and the ability to store hydrogen or CO2 in salt caverns to be essential factors for establishing a hydrogen cluster, in terms of infrastructure. The access to a seaport indicator has a lower weight in the scoreboard because it seems that the import of (green) hydrogen is not yet crucial in this stage. The transport costs are high, and the hydrogen can be used by the local (heavy) industry.

The electricity grid in Europe generally provides a high level of reliability and it's spread throughout all parts of Europe (EURELECTRIC, 2013; ENTSO-E, 2019). One of the biggest upcoming challenges for the electricity grid will be to integrate the rising share of (variable) renewable energy into the network (EURELECTRIC, 2013). The quality of the electricity grid will not be included in the scoreboard, because it is spread throughout all different parts of Europe and because it generally has a high reliability. This means that there should not be significant differences in the quality of the electricity grid across the different study regions.

<u>Industrial activity</u>
50% of the industrial activity dimension is aimed at the two broad indicators that focus on electricity consumption and the share of industrial activities in the regional economy. The combination of these two factors gives an indication of the energy consumption of the industrial sector in each region. These two indicators were used because there was no data available on the energy consumption of the regional industry in the correct spatial scale. The other 50% of this dimension is specifically aimed at the heavy industry in the region.

I used the regional employment share to gain insight in the size of the heavy industry in each region. There was no data available for either the regional energy consumption of heavy industry or their CO2 emissions, but these would have been more reliable indicators for this dimension. To determine the size of the regional heavy industry, I use the share of employment in the following heavy industries: chemicals, other non-metallic minerals (cement) and basic metals (iron & steel). The other non-metallic minerals category does not include the rubber and plastic industries. Also, when a region has a large chemical industry, this means that there might also be potential demand for the oxygen that is generated during the electrolysis process.

The structural business statistics by NUTS 2 regions from Eurostat (2021b) has missing data for some of the regions when it comes to the number of employees in the refinery industry, which means that this industry was not be included in the analysis. In addition, regional data for South Tyrol is missing for all the heavy industry types. This means that South Tyrol will not receive a rating on this dimension. However, I have imputed the data on the number of employees in the chemical industry for this region. This was imputed based on a report by Federchimica (2019) with contains data on the chemical industry in Italy. Their data, which shows the employees in the chemical industry for the Trentino-South Tyrol region in 2016, was used to estimate the number of employees for South Tyrol based on the population of Trento and South Tyrol, which was retrieved from Eurostat (2021b). In addition, data was missing on the number of employees in the basic metal industry in the province of Zeeland. The number of employees in this industry was imputed for Zeeland based on the number of employees and firms in this industry in West Netherlands and the number of firms in this industry in Zeeland. This data was retrieved from Eurostat (2021b).

The share of industrial activities in the total gross value added (GVA) indicator is used because it is assumed that more industrial activity will lead to more energy consumption, which could also lead to more potential demand for (green) hydrogen. In addition, it is assumed that regions with a high degree of manufacturing will also be more suitable for industrial activities like the production of hydrogen.

The regional data regarding the industrial energy demand was not available in the correct spatial scale. Instead, I use the total electricity consumption indicator. However, this variable also includes the electricity consumption of households, which means that more densely populated areas will almost certainly get a higher rating. More electricity consumption in the region could again lead to more demand for (green) hydrogen in order to fulfill the regional energy demand. These three indicators all have their drawbacks. However, the combination of these indicators should lead to a reliable rating on this dimension for each region.

<u>Innovation</u>

The development and diffusion of knowledge can be measured with indicators such as: number of patents applications, number of scientific publications and the (governmental) expenditures on R&D (Madsen and Andersen, 2010; European Union, 2019). I was unable to use regional patent data that was specifically related to renewable energy, because it either had the wrong spatial scale (OECD) or it did not include the relevant patent categories (Eurostat). In addition, the most recent EPO patent data that had no missing values was from 2012 (Eurostat). It should be noted that national patent systems co-exist with the European patent framework (Eurostat, 2019). I do not have access to the data on national patents. However, if this data would be included, then it could lead to different results on the innovation ratings.

Two different data sources were used for the R&D expenditure indicator, because they both had different missing values. For this I used the Regional Innovation Scoreboard 2019 by the European Commission (2019) and data from Eurostat (2021b). The scores of North Germany and the Northern Netherlands are solely based on the data from Eurostat (2021b). The two French regions only use the Regional Innovation Scoreboard 2019 data. Aragon, South Tyrol and North West England use the average scores of both sources. The Schelde-Delta region uses a different source for each region. Its score is then calculated and weighted based on each region's population in 2019.

<u>Industrial land price</u>

Industrial land price is another factor that can influence a firm's location behavior because firms that have lower rents are more profitable. Unfortunately, there is no data available for the industrial land price in European regions. Furthermore, land price is often not included in industrial location studies. Arauzo-Carod *et al.* (2010) compared 53 studies on industrial location, and only 5 studies included land price in their analysis. This could mean that land price is not that important for industrial location decisions, or that data regarding industrial land price are unavailable (CPB, 2015).

However, a region's population density can give some insight into the demand for (industrial) land. The CPB (2015) found a correlation of 0,79 between residential and industrial land prices. One explanation of this correlation is that firms often want to locate near consumers and employees. It is assumed here that regions with more demand for land (areas with higher population densities) have higher land prices. In addition, the amount of available land is more scarce in regions that are more densely populated. By taking the population density of each region into account we will get a more balanced picture of their agglomeration economies, by also taking its negative effects into account. Furthermore, heavy industry is often located in areas with low population density, because of their negative externalities. A hydrogen cluster can be established near these large energy consumers, which could be another advantage of producing hydrogen in a less densely populated region.

The OECD (2011) classifies regions as ‘rural’ when their population density is below 150 inhabitants per square kilometre. The means that we consider the four regions in France, Spain and Italy to be rural. This should be taken into account, especially when comparing the scores of the hydrogen regions on the transportation & infrastructure and the industrial activity dimensions. The population density has a significant influence on the density of the gas pipeline network (transportation & infrastructure) and on the total electricity consumption in the region (industrial activity).

6. Results

In this chapter I show and analyze the scoreboard ratings of the study regions. Table 5 shows the resulting scores on the different dimensions for each of the study regions. South Tyrol does not have a rating on the industrial activity dimension, because it had missing values on the employment share in several heavy industries. The scores on all the separate indicators are shown in Appendix B. When interpreting the scoreboard, it should be kept in mind that the ratings can be sensitive to changes in the weights. It could be the case that the rating can be just between two absolute values. For example, Aragon's rating on human capital is 1,49, which means that it barely gets a score of 1 in the scoreboard. Also, the Northern Netherlands has a 4,5 on transportation & infrastructure, which means that it barely got a 5. Appendix B shows the final ratings with 1 decimal.

Table 5: Results from the scoreboard

Region	**Natural resources**	**Human capital**	**Transportation & Infrastructure**	**Industrial activity**	**Innovation**	**Population density***
North Germany	3	4	4	4	4	174
Aragon	4	1	2	3	2	28
Normandy	2	4	3	2	3	111
Auvergne-Rhône-Alpes	2	4	3	2	5	114
South Tyrol	1	3	2	x	2	72
North Netherlands	4	3	5	3	2	205
Schelde-Delta	3	4	4	5	4	398
North West England	4	3	3	3	2	517

*The population density is the number of inhabitants per square kilometer, based on the total land area in 2016 and the population of 2019. This data was retrieved from Eurostat (2021b).

There are two regions that seem to be in the best position for establishing a hydrogen cluster: the Schelde-Delta region and North Germany. They do not have any insufficient scores and they have an average rating of 4. Their ratings are very similar, but the Schelde-Delta region has a higher rating on the industrial activity dimension. Both regions have a relatively high amount of electricity generation from natural gas and they both have potential for green electricity from offshore wind. Both have good scores on human capital. In North Germany there is a high share of the population that is employed in science and technology. Also, a large share of the young people in the Schelde-Delta region have completed either a vocational or tertiary study program. The Schelde-delta region has the densest gas pipeline network of all the study regions. However, this is also influence by its high population density. One drawback of the Schelde-Delta region is that there are no suitable salt caverns for H2 or CO2 storage in the region. Unlike North Germany which does have suitable salt caverns for the storage of H2 or CO2. Both regions also have high degrees of industrial activity. The Schelde-Delta region has a very high electricity consumption and a large labor pool in heavy industries. However, it should be kept in mind that its high electricity consumption is also heavily influenced by its high population density. Also, industrial activities constitute a relatively large share of North Germany's GDP. Both regions also have a relatively high level of innovation, with both high R&D expenditures and high amounts of EPO patent applications.

The Northern Netherlands is one of the four regions that can be characterized as the middle performers. The regions in this group have an average rating of 3 and 1 or 2 insufficient scores. The Northern Netherlands excels in the natural resources dimension, due to its high potential for offshore wind. It also has a high score on transportation & infrastructure, because of its dense gas pipeline network and the availability of salt caverns for H2 or CO2 storage. The Northern Netherlands has an average score on the human capital dimension. It has the lowest employment share in the electricity, gas and other related sectors out of all the hydrogen regions. However, this is compensated by the relatively high employment share in science and technology and the region's education level. The Northern Netherlands also has an average score on the industrial activity dimension. Industrial activity constitutes a large share of its economy, but the region has a relatively small employment share in heavy industries. One weakness of the Northern Netherlands is its relatively low score on innovation. This is due to its very low amount of EPO patent applications, compared to the other Hydrogen Valleys. The Northern Netherlands has similar ratings as the North West England region, but the Northern Netherlands has a higher score on the transportation & infrastructure dimension.

The other two middle performers are the two French regions. Their ratings show a similar pattern; they both have low ratings on the natural resources and industrial activity dimensions. They both have no significant electricity generation from natural gas. Furthermore, Auvergne-Rhône-Alpes has the lowest potential for green electricity per 10.000km2. It does not seem to have the suitable geographical conditions that are necessary for green electricity production. However, Auvergne-Rhône-Alpes does have a high absolute amount of potential for green electricity, but this is mainly due to the fact that it is one of the largest NUTS 1 regions in terms of area in this comparison. Furthermore, both regions have relatively low electricity consumption, but this can also be explained by their lower population density. Normandy has the lowest share of employment in heavy industries out of all the regions. The two French regions both have high scores on human capital. They both have a large labor pool in the sectors of electricity, gas, steam, air conditioning, water and construction, and Auvergne-Rhône-Alpes is the region with the largest share of young people that completed either a vocational or tertiary study program. Auvergne-Rhône-Alpes is also the most innovative region in this comparison; with both the highest R&D expenditures and the most EPO patent applications per capita.

Aragon and South Tyrol have the lowest ratings in this comparison. They have an average rating of 2 and they both have 3 insufficient scores. They also both have a dimension with a rating of 1. Both have a low score on transportation & infrastructure and innovation. These regions also have the least dense gas pipeline networks. However, this could also be caused by the fact that they are also the least densely populated regions in this comparison. Furthermore, both regions are landlocked, and they also do not have ports. South Tyrol has a relatively good score on the number of EPO patent applications, but it has the lowest R&D expenditure of all the hydrogen regions. South Tyrol has a very low score on the natural resources dimension, which is essential for (green) hydrogen production. Aragon has a high score on this dimension, because it has high potential for green electricity from onshore wind and solar panels. However, Aragon has a very low score on human capital. It has the lowest share of employees in science and technology and the lowest share of young people that completed either a vocational or tertiary study program in this comparison. The generally low scores of South Tyrol create doubts about the region’s intention to be a Hydrogen Valley.

7. Conclusion

The Northern Netherlands is one of the middle performing hydrogen regions in this analysis. It has comparative advantages in its high potential for offshore wind and it also has existing infrastructure that can be adapted and used for green or blue hydrogen transportation and storage. However, in terms of innovation it lags behind other Hydrogen Valleys. This is due to its relatively low amount of EPO patent applications. This makes it important for regional policy makers to stimulate innovative start-ups and scale-ups in the region. Especially, those that want to work with hydrogen technology. Also, the relatively low level of innovation does not mean that the Northern Netherlands cannot become a successful Hydrogen Valley. A strategy that this region could take would be to focus on large scale green hydrogen production from offshore wind, instead of focusing for example on the research and development surrounding (green) hydrogen technology. This should probably be left to the regions that have a higher rating on the innovation and human capital dimensions. These are Auvergne-Rhône-Alpes, the Schelde-Delta region and North Germany.

It is probable that the Northern Netherlands will face tough competition from North Germany and the Schelde-Delta region. These two regions are located close to the Northern Netherlands and they both have the highest ratings on the scoreboard overall. The Northern Netherlands should play to its strengths by exploiting the fact that it has a higher potential for green electricity than these competing regions. The Northern Netherlands also has a comparative advantage in terms of transportation & infrastructure. It has a denser gas pipeline network than North Germany, and the Schelde-Delta region does not have suitable underground storage facilities for hydrogen or CO2. In addition, the Schelde-Delta region is more densely populated than the Northern Netherlands, which could also mean that the land prices are higher in the Schelde-Delta region. This also means that there should be more free space available in the Northern Netherlands for constructing large electrolyzers. This aspect could give the Northern Netherlands a competitive edge over the other hydrogen clusters in the Netherlands and Belgium that are located in more densely populated areas (the Schelde-Delta region and Rotterdam).

The positive result for North Germany could mean that when we look at the strengths of its individual states, that the ratings will be even higher. North Germany covers five German states which all have their own advantages for creating a sustainable hydrogen industry. For example, from the scoreboard data it becomes clear that Hamburg has the highest share of employment in science and technology and the most EPO patents per capita out of all the study regions. Bremen has a large employment share in the metal industry. Mecklenburg-Vorpommern has the highest share of employment in electricity, gas, steam, air conditioning, water and construction. Finally, Lower Saxony has the highest share of Gross Value Added (GVA) from industrial activities.

It also interesting to note that the lowest performing regions in this scoreboard (Aragon and South Tyrol) also seemed to have the least concrete information about their hydrogen ambitions available on the internet. In case of Aragon, it should however be noted that it is the only region in this research that is not present on FCH JU's Hydrogen Valley platform. Overall, there was less information available (in English) for the Hydrogen Valleys that are located in Romance-speaking countries. This could have led to a slight bias in the scoreboard towards the Hydrogen Valleys that have published more information about their intentions to invest into green or blue hydrogen.

Future research could focus on the planned transnational hydrogen projects in the European Union. I have not analyzed these projects in the research, due to the regional perspective of this research. However, it could be relevant to compare these large transnational projects with the Hydrogen Valleys that were analyzed in this research. For example, by comparing these two different approaches and to analyze the strengths and weaknesses of each approach. Another recommendation for future research would be to assess the role of the regional institutions in the Hydrogen Valleys. For example, by mapping the regional hydrogen policies and other support schemes that are in place to support the development of a (green) hydrogen cluster in their respective regions. Other future research could also focus on the importance of industrial land price for the establishment of a hydrogen cluster, because it is not yet clear to what extent this aspect influences the location behavior of firms in this specific industry.

As has already been said throughout the methodology chapter, I was unable to use the preferred indicators for all of the dimensions because that specific data was not always available. For example, in the natural resources dimension I used the electricity generated from natural gas, instead of the production of natural gas. The industrial activity dimension should have had an indicator on the industrial energy consumption of each region. The size of the heavy industry would have been a more reliable indicator if it was measured by the share of the regional GDP or by its CO_2 emissions, instead of measuring it with the employment share. Also, the innovation indicator should have focused on the patents and R&D expenditure specifically in the renewable energy sector.

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Title page figure

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Appendices

A. Information about the selected hydrogen regions

Information about each Hydrogen Valley was retrieved from diverse internet sources and some regional hydrogen plans that were published (Table 6).

Table 6: Available regional hydrogen plans

Region	Plan	Source
North Germany	Hydrogen Strategy for North Germany	Ministries of Economy and Transport of the North German States (2019)
Aragon	Hydrogen Master Plan 2016-2020	Foundation for the development of new hydrogen technologies in Aragon (2016)
Normandy	Normandy Hydrogen	Région Normandie (2020)
Auvergne-Rhône-Alpes	N.A.	N.A.
South Tyrol	N.A.	N.A.
North Netherlands	The Northern Netherlands Hydrogen Investment Plan 2020	New Energy Coalition *et al.* (2020)
Schelde-Delta	Regional plan 2030-2050	Smart Delta Resources (2020)
North West (UK)	HyNet North West Vision	HyNet North West (2020)

Northern Netherlands

The Northern Netherlands is in a good position to take a leading role in the upcoming hydrogen revolution, due to the Wadden Sea and the North Sea, which are characterized by **high wind speeds** (van Wetering, 2019). Another advantage is the **gas infrastructure** and gas storage fields that are present in the area. The region has also acquired the relevant **knowledge** in the fields of gas extraction and transport (ibid).

The advantages of the Northern Netherlands, according to New Energy Coalition *et al.* (2020):

- Large offshore wind potential north of Northern Netherlands, with available space for over 20 GW of which 4 to 6 GW of hydrogen-dedicated wind is required by 2030
- Available and dense gas infrastructure, with high-quality parallel gas pipelines, salt caverns for hydrogen **storage**, and strategically located **ports**
- Gas and hydrogen knowledge, on gas trading, transport and innovation, that builds on the Dutch position as the European leader in natural gas excellence and ongoing hydrogen projects

The Northern Netherlands has been recognized as the leading Hydrogen Valley in Europe. Building on this current momentum, recognition, and ambition level, it aspires to remain the leading European hydrogen ecosystem beyond 2030, covering the entire hydrogen value chain, including offshore wind (at least 4 to 6 GW), hydrogen production (over 65 PJ/a clean production), transport (1.150 km of connected Northwestern European hydrogen pipelines), storage (150 PJ potential), and demand in Northwestern Europe (400 PJ per annum from Benelux, Western Germany, and Northern France) (New Energy Coalition *et al.*, 2020). By 2030, the Northern Netherlands will produce approximately 100 PJ of hydrogen per annum to supply over 25 percent of the hydrogen demand of Northwestern Europe. Beyond 2030, when the European hydrogen ecosystem is fully developed, the Northern Netherlands will be the global center of hydrogen infrastructure and expertise, renewing its role as a leading "gas roundabout" and market hub for green fuels, manufacturing excellence, knowledge, and innovation (ibid).

Six reasons for hydrogen production in Groningen (König, 2021):
1. High wind speeds / **wind energy potential**
2. Enough **space** for large electrolyzers
3. Densest **gas network** of Europe
4. Regional demand for hydrogen
5. Storing hydrogen in **salt caverns** in Zuidewende, which is close Delfzijl
6. **Knowledge** related to gas, which is related to hydrogen

The Energy Academy Europe in Groningen is the new top institute where energy education, research and innovation meet (Campus Groningen, 2017). The EAE is an initiative of the University of Groningen and the Hanze University of Applied Sciences. The main energy issues of the EAE are gas (including biogas and green gas), tomorrow's energy (such as wind and solar), smart grids, energy efficiency and savings and CO2 reduction. The EAE is open to all people, organizations and companies that want to work with reliable, sustainable and affordable energy (ibid).

Hydrogen Delta (Zeeland)

The SDR region consists of the provinces of Zeeland and East Flanders and West Brabant (Smart Delta Resources, 2020). The region is the largest hydrogen producer and consumer in the Netherlands and Flanders (Smart Delta Resources, 2021). The region has a strong starting position for large-scale, rapid implementation of green hydrogen production. Current hydrogen consumption (580 kton H2/year) in the region covers more than a third of Dutch industry. The region already has a large-scale, flexible range of **steam reformers** (SMRs) to 'smooth out' non-continuous green hydrogen output from electrolyzers. The **oxygen** produced during the electrolysis can also be sold locally at steel producer ArcelorMittal, Zeeland Refinery, Dow and Yara, among others (ibid).

The region is conveniently close to various renewable energy supplies. The rapid landing of offshore wind energy will give the region direct access to thousands of megawatts of **wind energy** (Smart Delta Resources, 2021). In addition, there is access to CO2-neutral electricity for the production of hydrogen through the **nuclear power** plant in Borsele. In addition, the region currently already has a high-quality gas / 380 kV electricity infrastructure in the Sloe area (Vlissingen) and Rodenhuize (Ghent). In addition, there are excellent opportunities for connection to a national H2 backbone and for realizing a hydrogen hub in the port area of North Sea Port with opportunities for **import**, storage and transit of hydrogen (ibid).

North Germany

The departments for business development of the five federal states of Bremen, Mecklenburg-Vorpommern, Lower Saxony, Schleswig-Holstein and Hamburg have joined forces to form the green hydrogen initiative HY-5 (Ministries of Economy and Transport of the North German States, 2019). Their aim is to promote the economic development of green hydrogen. North Germany features the following locational advantages for establishing a ‘green’ hydrogen economy (ibid):
- Great generating capacity for onshore and offshore **wind-generated electricity** with further expansion potential
- **Underground formations** for storing hydrogen
- **Seaports** whose import terminals are going to play a decisive role as logistics and business hubs, when it comes to importing and distributing green hydrogen, as well as for exporting hydrogen-related technology and components
- Maritime enterprises and scientific expertise
- **Industry** sectors with significant experience in handling hydrogen

Auvergne-Rhône-Alpes

Hympulsion is now operational and will help speed up deployment of the Zero Emission Valley. This is France's first renewable hydrogen-driven mobility project for professional captive fleets, which includes 1.000 vehicles and 20 hydrogen refueling stations (Fuel Cells Bulletin, 2019). The project, co-financed by European funding, will provide vehicles and green hydrogen at an overall cost on a par with diesel. The sheer scale of this project means that it will provide 25% of the vehicles announced in the national hydrogen plan by 2023. With 80% of the French hydrogen sector stakeholders located in Auvergne-Rhône-Alpes, developing hydrogen-driven mobility will give momentum to this premium industrial sector and help ensure its longevity (ibid).

Thanks to its industry and research stakeholders, Auvergne-Rhône-Alpes region is one of the most dynamic and **innovative** regions in France, ranking just after the Paris Ile de France region on many innovation indicators (European Commission, 2021a). Auvergne-Rhône-Alpes is the first French region for energy production as a whole and leads in particular for nuclear and renewable energy production. In terms of **human resources**, the percentage of jobs in high-technology sectors represented 4,2% of the total employment in 2017. In terms of **patent** applications, Auvergne-Rhône-Alpes is a good performer, and the region accounted for 21,7% of France's patent applications in 2012. Auvergne-Rhône-Alpes research has a strong focus on physics, electronics, **chemistry**, energy and transportation, and sectors on the rise include life sciences and environment. Mechanical engineering, biotechnologies, ICT, and eco-technology industries are also regional key industries. A dense network of regional innovation stakeholders is contributing to public-private research collaborations. The **University** of Lyon is the main French higher-education and scientific center outside of the Paris region, The university has three strategic domains: biology health and society; science and engineering for a sustainable society and urbanism and humanities (ibid).

Normandy

Almost a third of the national **hydrogen consumption** takes place in Normandy, in particular in the petrochemical sector as well as on the Ariane Group test site (Région Normandie, 2020). The Normandy Region was the first French region to adopt its support plan for the hydrogen sector in October 2018. This plan has a budget of 15 million euros for three years (ibid). Also, in Normandy the H2 Academy project was initiated to provide training within the region to develop the skills that are required for the hydrogen sector (ibid).

Normandy has the natural assets (wind, biomass, etc.) that are needed for the development of renewable energy and hydrogen. Normandy also has (Région Normandie, 2020):

- 2 major **sea ports** (Le Havre and Rouen) and 3 regional ports
- A logistical region welcoming significant numbers of goods and passengers
- A maritime region with the most renewable marine energy potential in France
- Well-honed skills linked to the production, consumption and handling of hydrogen (petrochemical, **chemical**, aerospace)
- An industrial region with significant **hydrogen consumption**

North West England

The North West of England is poised to be one of the primary regions for the development of a decarbonized, hydrogen-based energy market for the UK (North West Hydrogen Alliance, 2021). It already features all the necessary components to develop a hydrogen economy – thriving industry, an existing **skilled workforce**, city regions that collaborate, as well as natural and industrial assets. This leading energy powerhouse is made up of Manchester, Liverpool, Warrington, Chester, Lancashire and Cumbria (ibid). In addition, the North West boasts the largest concentration of advanced manufacturing and chemical production in the UK and is home to a concentration of **energy intensive users** (Net Zero North West, 2020).

Esteemed **universities** and a wealth of innovative research companies mean the region is delivering world first hydrogen technologies. With academia working side by side with industry, the North West's institutions can equip the next generation of skilled workers to support the hydrogen economy (North West Hydrogen Alliance, 2021).

Key **infrastructure,** such as the Manchester Ship Canal and the **Port** of Liverpool, offer gateways to hydrogen transportation (North West Hydrogen Alliance, 2021). These facilities give nearby petrochemical facilities a strategic advantage in the development of carbon utilization technologies; producing cleaner fuels, polymers and other materials; reducing the amount of CO2 sent for storage. Geologically, Cheshire is one of the few places in the UK where **underground gas storage** in salt caverns has been delivered, paving the way for potential hydrogen storage. Offshore facilities in the East Irish Sea can also store CO2 produced from hydrogen reforming. Across the region, operational hydrogen production facilities are primed to deliver; and **existing pipelines** are ready for repurposing (ibid).

Aragon

In the field of hydrogen production, Aragon has some strengths: abundant **renewable resources**: sun, wind, water and territory, taking place a surplus electrical renewable production in the region (HyER, 2019). In this scenario the hydrogen foundation in Aragon, as the driving force in hydrogen technologies in the region, is supported by the most important energetic companies of the region, which form part of its council. The main productive industrial sectors in Aragon are: **energy**, automotive, **chemical**, metal mechanical, logistics and electronics (Foundation for the development of new hydrogen technologies in Aragon, 2016).

South Tyrol

There are many **hydropower** plants in South Tyrol. By converting this electrical energy - which is not needed locally - into hydrogen, this green electricity can be stored and, among other things, can also be used in the mobility sector (Institute for Innovative Technologies Ltd, 2021). The manufacturing specializations of this region are heavy vehicles and the **steel** industry (European Commission, 2021b)

B. Detailed version of the hydrogen scoreboard

Key figures

	Population (2019)	Total area in km2 (2016)
East Flanders	1.516.283	3.009
Bremen	682.986	420
Hamburg	1.841.179	755
Mecklenburg-Vorpommern	1.609.675	23.293
Lower Saxony	7.982.448	47.710
Schleswig-Holstein	2.896.712	15.802
Aragon	1.320.586	47.722
Normandy	3.320.832	30.113
Auvergne-Rhône-Alpes	8.030.533	71.134
South Tyrol	530.313	7.398
North Netherlands	1.723.829	9.082
Zeeland	383.032	1.935
North West (UK)	7.300.075	14.164

Eurostat

Population density 2019

North Germany	174
Aragon	28
Normandy	111
Auvergne-Rhône-Alpes	114
South Tyrol	72
North Netherlands	205
Schelde-Delta	398
North West (UK)	517

Natural resources

Potential green electricity in TWh per 10.000km2

	75%	*min-max*	*percent rank*	
North Germany	33,8	*0,5*	*0,6*	3,2
Aragon	56,7	*1,0*	*1,0*	5,0
Normandy	30,1	*0,4*	*0,4*	2,7
Auvergne-Rhône-Alpes	20,2	*0,2*	*0,1*	1,7
South Tyrol	9,8	*0,0*	*0,0*	1,0
North Netherlands	41,4	*0,7*	*0,7*	3,8
Schelde-Delta	26,5	*0,4*	*0,3*	2,3
North West (UK)	52,2	*0,9*	*0,9*	4,5
Kakoulaki et al.	*min*	*9,8*		
	max	*56,7*		

Electricity generated from natural gas in 2020 (forecast)

	25%	**Rating**
North Germany	4	**3,4**
Aragon	1	**4,0**
Normandy	1	**2,3**
Auvergne-Rhône-Alpes	1	**1,5**
South Tyrol	1	**1,0**
North Netherlands	3	**3,6**
Schelde-Delta	4	**2,7**
North West (UK)	3	**4,1**

Joint Research Centre

Human capital

% of total workforce employed in electricity, gas, steam, air conditioning, water or construction (2019)

	40%	*min-max*	*percent rank*	
North Germany	8,3	*0,6*	*0,6*	3,4
Aragon	7,7	*0,5*	*0,1*	2,2
Normandy	9,7	*1,0*	*1,0*	5,0
Auvergne-Rhône-Alpes	9,0	*0,8*	*0,9*	4,3
South Tyrol	8,7	*0,7*	*0,7*	3,9
North Netherlands	5,9	*0,0*	*0,0*	1,0
Schelde-Delta	8,2	*0,6*	*0,3*	2,8
North West (UK)	8,3	*0,6*	*0,4*	3,1
Eurostat	*min*	*5,9*		
	max	*9,7*		

% of population employed in science and technology (2019)

	25%	*min-max*	*percent rank*	
North Germany	27,0	*1,0*	*1,0*	5,0
Aragon	16,6	*0,0*	*0,0*	1,0
Normandy	18,4	*0,2*	*0,1*	1,6
Auvergne-Rhône-Alpes	23,9	*0,7*	*0,4*	3,3
South Tyrol	19,5	*0,3*	*0,3*	2,1
North Netherlands	25,9	*0,9*	*0,9*	4,5
Schelde-Delta	24,0	*0,7*	*0,6*	3,6
North West (UK)	24,1	*0,7*	*0,7*	3,9
Eurostat	*min*	*16,6*		
	max	*27,0*		

% of 25- to 34-year-olds that completed education (2019)

	Vocational	Tertiary	**35%** Total	*min-max*	*percent rank*		**Rating**
North Germany	**50,3**	28,0	78,3	*0,8*	*0,4*	3,5	**3,9**
Aragon	15,7	**47,8**	63,5	*0,0*	*0,0*	1,0	**1,5**
Normandy	**43,3**	35,1	78,4	*0,8*	*0,6*	3,8	**3,7**
Auvergne-Rhône-Alpes	30,0	**51,1**	81,1	*1,0*	*1,0*	5,0	**4,3**
South Tyrol	**45,3**	25,0	70,3	*0,4*	*0,1*	2,1	**2,8**
North Netherlands	37,4	41,2	78,6	*0,9*	*0,7*	4,1	**3,0**
Schelde-Delta	34,1	**45,9**	80,0	*0,9*	*0,9*	4,6	**3,6**
North West (UK)	25,1	**45,3**	70,4	*0,4*	*0,3*	2,4	**3,0**
Eurostat			*min*	*63,5*			
			max	*81,1*			

Transportation & Infrastructure

km gas pipelines per 10.000km2	40%	min-max	percent rank			H2/CO2 storage 35%	Sea access / Ports 25%		Rating
North Germany	816,3	0,5	0,7	3,3	North Germany	5	4	Sea: Hamburg	**4,1**
Aragon	216,7	0,0	0,1	1,3	Aragon	4	2	x	**2,4**
Normandy	588,6	0,3	0,6	2,7	Normandy	2	4	Sea: Le Havre	**2,8**
Auvergne-Rhône-Alpes	462,6	0,2	0,3	1,9	Auvergne-Rhône-Alpes	4	3	1 port: Lyon	**2,9**
South Tyrol	210,0	0,0	0,0	1,0	South Tyrol	2	2	x	**1,6**
North Netherlands	1356,1	0,9	0,9	4,4	North Netherlands	5	4	Sea: Eemshaven	**4,5**
Schelde-Delta	1552,0	1,0	1,0	5,0	Schelde-Delta	2	4	Sea: Vlissingen	**3,7**
North West (UK)	561,2	0,3	0,4	2,4	North West (UK)	4	4	Sea: Ellesmere port	**3,4**
SciGRID_gas	*min*	*210,0*				*GIE*	*Eurostat*		
	max	*1552,0*							

Industrial activity

Total electricity consumption in TWh per 10.000km2 (2019)	25%	min-max	percent rank		% of total GVA by industry (2018)	25%	min-max	percent rank	
North Germany	17,1	0,6	0,7	3,6	North Germany	23,1	1,0	1,0	5,0
Aragon	1,5	0,0	0,0	1,0	Aragon	21,6	0,8	0,7	3,9
Normandy	7,9	0,2	0,3	2,1	Normandy	20,4	0,6	0,4	3,0
Auvergne-Rhône-Alpes	8,2	0,3	0,4	2,4	Auvergne-Rhône-Alpes	18,2	0,2	0,3	2,1
South Tyrol	3,3	0,1	0,1	1,4	South Tyrol	16,7	0,0	0,0	1,0
North Netherlands	13,6	0,5	0,6	3,1	North Netherlands	22,9	1,0	0,9	4,7
Schelde-Delta	27,2	1,0	1,0	5,0	Schelde-Delta	21,1	0,7	0,6	3,5
North West (UK)	23,8	0,9	0,9	4,4	North West (UK)	17,9	0,2	0,1	1,7
Kakoulaki et al.	*min*	*1,5*			*OECD*	*min*	*16,7*		
	max	*27,2*				*max*	*23,1*		

Employees in heavy industries / 1.000 employed people (2018)

	Chemical	Non-metallic mineral (other)	Basic metals	50% Total	min-max	percent rank		Rating
North Germany	6,0	4,2	4,4	14,7	*0,4*	*0,7*	3,2	**3,7**
Aragon	**7,0**	**6,4**	4,1	17,5	*0,6*	*0,8*	3,9	**3,2**
Normandy	3,5	2,6	2,5	8,7	*0,0*	*0,0*	1,0	**1,8**
Auvergne-Rhône-Alpes	4,9	4,2	2,5	11,7	*0,2*	*0,3*	2,1	**2,2**
South Tyrol	3,4	:	:	:	*:*	*:*	:	**x**
North Netherlands	5,5	3,4	1,6	10,4	*0,1*	*0,2*	1,6	**2,7**
Schelde-Delta	**11,0**	4,1	**7,8**	23,0	*1,0*	*1,0*	5,0	**4,6**
North West (UK)	**7,1**	2,8	4,2	14,1	*0,4*	*0,5*	2,8	**2,9**
Eurostat	imputed		data from 2017	*min*	*8,7*			
				max	*23,0*			

Innovation

Rating of public and private R&D expenditures (2017/2019)

	50%
North Germany	4,5
Aragon	2,0
Normandy	3,0
Auvergne-Rhône-Alpes	5,0
South Tyrol	1,0
North Netherlands	3,1
Schelde-Delta	4,3
North West (UK)	3,2

Based on Eurostat & European Commission

EPO patent applications per million inhabitants (2012)

	50%	min-max	percent rank		Rating
North Germany	143,7	*0,7*	*0,9*	4,1	**4,3**
Aragon	54,0	*0,1*	*0,3*	1,8	**1,9**
Normandy	65,0	*0,2*	*0,4*	2,2	**2,6**
Auvergne-Rhône-Alpes	194,3	*1,0*	*1,0*	5,0	**5,0**
South Tyrol	125,0	*0,6*	*0,7*	3,5	**2,3**
North Netherlands	39,3	*0,0*	*0,1*	1,3	**2,2**
Schelde-Delta	113,7	*0,5*	*0,6*	3,1	**3,7**
North West (UK)	39,2	*0,0*	*0,0*	1,0	**2,1**
Eurostat	*min*	*39,2*			
	max	*194,3*			