University of Groningen

Bachelor Thesis Project

Hydrogen in the European energy transition:

Where will it come from?

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Abstract

Putting a hold on climate change will be one of the biggest challenges of the next couple of decades. Right now we are at the start of a very big energy transition from fossil to renewable energy. Hydrogen will play a crucial role in this transition. Hydrogen can be used as an energy carrier, to store or transport energy and hydrogen can be used in hard to decarbonize sectors that cannot be decarbonized using green electrical power. Ways have to be sought after to produce hydrogen in big quantities without CO_2 emissions. This thesis investigates how the EU is going to realize this hydrogen production (10 million tonnes in 2024 and 40 million tonnes in 2030) and how the EU will ensure that hydrogen is able to compete with fossil fuels, since to this day fossil fuels are much cheaper. This literature review is executed by reviewing governmental documents, publications of the European Commission and scientific literature. Hydrogen will be produced using electrolysis powered by renewable energy. Electrolysers will be built and renewable energy production will be scaled up rapidly to make up for the increase in demand. Collaborations are formed between multidisciplinary companies like The Green Hydrogen Alliance and the HyDeal Ambitions. To support this further many subsidizing plans have been announced. Despite that, clear and concrete implementation of the plans seem to be lacking. This is partly because many concrete actions are still under consideration of the European Commission and the feel of urgency does not seem to be present among many politicians. Politicians and governments need to act now, for the climate goals of 2030 and 2050 still to be achievable.

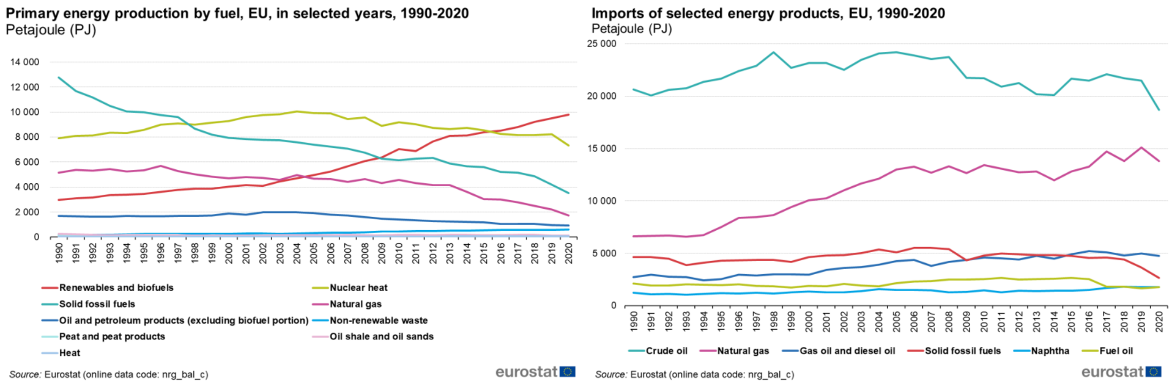
Contents

1 Introduction

Climate change is one of the biggest problems in the world that has to be tackled in the next couple of decades. Temperatures and ocean levels are rising, and the weather in general is becoming more extreme. This poses direct dangers like climate disasters, and indirect dangers like big famines caused by the fact that harvesting crops may become more difficult because of the changing climate. Carbon dioxide emissions play a major role in climate change and the warming of our planet. CO_2 traps heat coming in as radiation from the sun in our atmosphere. In the first instance this made life possible on earth, since some trapping heat is key for the temperature and thus life on earth. But by emitting vast quantities of CO_2 every day, this trapping of heat increases, leading to a rising average temperature on earth. This is why carbon emission has to be decreased rapidly and why the EU even plans to be CO_2 neutral by 2050 [1]. Meaning that there are no net carbon emissions by that time. Many innovations are being made regarding renewable energy to get away from our fossil fuel based world. Hydrogen is enjoying an increasing attention in this context. Hydrogen may be used as fuel and as a way to store and transport energy. This is because Hydrogen can carry lots of energy by weight and does not emit any CO_2 when being used. The EU has set ambitious hydrogen production goals for the next decades, to shift our fossil fuel based world to a hydrogen based world. A very import aspect in this transition is the question where all this hydrogen has to come from, since it has to be produced in a way. **The aim of this thesis is to determine how the European Union intends to reach its set hydrogen production goals in the next decades.** In this section the current energy situation in Europe will be elaborated in general and with regards to hydrogen.

Renewable energies account for the highest share in energy production in the EU, more than 40% of produced energy is renewable[3]. 40% might sound very good and promising, but the majority of consumed energy is being imported from outside the EU. All energy that is imported is fossil. For this reason still 85% of all consumed energy in the EU is from carbohydrates [2]. Figure 1 shows the share of different kinds of energy that is being produced (a) and imported (b) from 1990 to 2020 for the European Union as a whole.

From the two diagrams one can conclude that the majority of consumed energy is being imported, and thus that the EU is far from independent when it comes to energy. For a transition to be made from carbon-based to green hydrogen based energy a lot has to be done. One positive note is that the amount of produced renewable energy keeps growing each year.



(a) (b)

Figure 1: Energy production and import in the EU, 1990-2020. Taken from ref. [3]

It is also relevant to look into where all this energy goes. For improvements to be made, a good general picture is necessary. Which sectors use the most energy and if the carbon-based energy can be replaced with hydrogen in some way is a very important question, since implementation of hydrogen as a fuel or energy carrier is more useful in some cases than in others. Figure 2 shows the share of energy consumption per sector. The biggest energy consumer is the transport sector. From this energy almost 90% was fossil in 2017 [4].

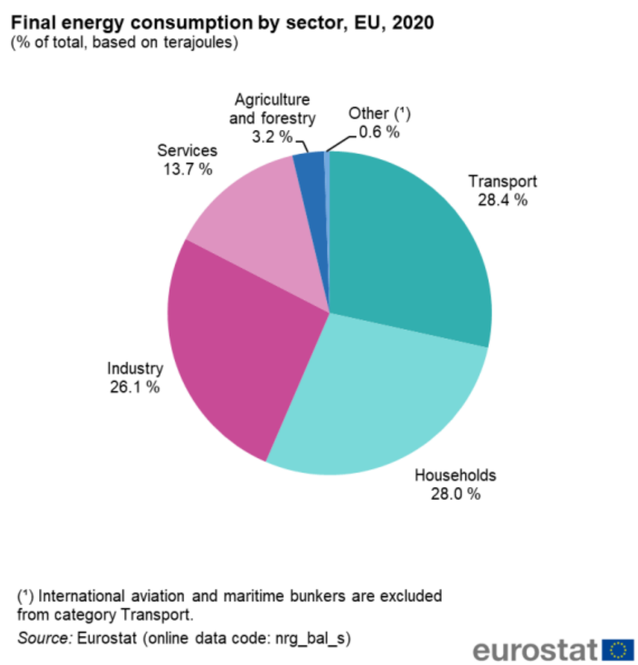


Figure 2: Energy consumption by sector, EU, 2020. Taken from ref. [3].

Hydrogen has great potential to play a big role in decarbonising the transport sector since some kind of fuel or energy carrier is needed in the most cases and pressurised hydrogen can carry lots of energy per liter, although not as much as gasoline.

Industry and households are the two other biggest consumers of energy. In industry there are some carbon intensive processes, like the production of steel and chemicals. Hydrogen can replace fossil fuels in some of those processes [1]. For households in the EU in 2019 almost 80% of the consumed energy was used for space and water heating, which is mostly done by using natural gas [5]. The question is if substituting natural gas by hydrogen in this case is preferable over using for instance green electrical power.

In 2015 the vast majority of produced and used hydrogen is being made from natural gas (48%), oil (30%) and coal (18%) emitting 70 to 100 million tons of CO_2 annually in the EU in the process [7][1]. Making these ways of producing hydrogen not renewable and far from carbon-neutral. Another way to produce hydrogen that is more carbon-friendly is by using electrolysis, which accounts for 4% of produced hydrogen to this day [6]. In this process electricity is used to split water molecules in to hydrogen and oxygen. The origin of the used electricity is of importance in determining the carbon-friendliness of the hydrogen. Since when the electricity originates form a coal-fired power station lots of CO_2 are still emitted in the process. When the electricity originates from a wind or solar powered source, almost no carbon-dioxide is emitted making this method very carbon-friendly and a good candidate to play a big role in the energy transition that is being made in the next couple of decades.

Hydrogen is a top priority to achieve the European Green Deal and for a smooth transition away from fossil fuels. Many indicators signal that we are now close to a tipping point. Every week new developments and investment plans are announced on the Giga Watt scale. Furthermore the number of companies that are in the International Hydrogen Council has grown from 13 in 2017 to 81 in 2020 [1]. It is expected that renewable energy is able to decarbonize a large share of the EU energy consumption. Hydrogen has great potential to bridge some of this gap. Hydrogen can be used for energy storage, leveling out daily and annual variations, transport and many more things.

To support this transition big changes have to be made in legislation to make renewable hydrogen cost competitive to fossil fuels, because the to this day small hydrogen economy has to compete with big multinationals like Shell and Aramco. Governmental help and subsidies are crucial in this transition.

2 Research Question

To make the transition from a carbon-based energy world to a renewable energy world many changes have to be made. One of which involves using green-hydrogen as an energy carrier in stead of using fossil fuels. The European Union has set ambitious hydrogen production goals for itself, which will completely transform the global energy consumption landscape in the next decades. This thesis will investigate how the EU is planning to properly execute this transformation from a carbon-based energy to a green-hydrogen based energy world. The research question that will be discussed in this thesis is the following:

> **How is the EU planning to reach the set hydrogen production goals in the next decades?**

To properly investigate the research question, four sub-questions were invented that help investigating the main topic. The answers to the sub-questions provide a framework in which the results to the research question can be presented and explained properly. These sub-questions will be elaborated on further in this section.

The first step in answering the is determining what the set hydrogen production goals are for the next decades. This leads to the following sub-question:

> Sub-question 1: **What are the hydrogen production goals of the EU in the next decades?**

A logical follow up question is where all this hydrogen has to come from. Which gives rise to the second sub-question:

> Sub-question 2: **How is the EU planning to produce the intended amounts of hydrogen?**

Despite the fact that producing enough green hydrogen may seem like the only challenge, hydrogen production is far from everything. There are many other things that this problem includes. The EU has to for example shape a landscape in which not only the supply but also the demand for hydrogen is raised, and while the green hydrogen industry is still in its infancy, 85% of all consumed energy on the world still comes from carbon-based sources[2]. The EU has to find ways to make green hydrogen cheaper and more appealing than it is now. Only then green hydrogen will be able to compete with carbon-based energy. Appropriately this leads to the following sub-question:

> Sub-question 3: **How is the EU planning to make hydrogen compete with carbon-based energy?**

The transition from carbon-based energy to green hydrogen is primarily being made for two reasons: Fossil fuels are running out and carbon emissions need to be significantly decreased to put a hold on climate change. The transition will be a process that can take several decades, which leaves the question if the transition can be made quickly enough or that other solutions to the prior stated reasons should be sought after. This gives rise to the last sub-question:

> Sub-question 4: **Is the transition from carbon-based energy to green-hydrogen based energy fast enough?**

In the Methodology section there will be elaborated on how this research will executed and how the answering of the research question and the posed sub-questions will be carried out.

3 Methodology

This research is a literature review and is carried out by investigating governmental documents, scientific literature and publications of the European Commission. Smart cat was used for finding and getting access to scientific literature. All documents of the European Commission are publicly available. When reviewing publications regarding quantitative data, technological developments and in specific the cost of fossil fuels (because of a very sudden rise partly caused by the war in Ukraine) the date of publication was always checked. Hezelburcht Grant Consultancy was contacted with questions regarding European subsidies.

4 Results

To properly formulate an answer to the research question, answering the sub-questions is essential to provide a good framework to work in. Therefore first all sub-questions will be answered subsequently, after which the research question will be addressed.

4.1 Sub-question 1: What are the hydrogen production goals of the EU in the next decades?[1]

The first sub-question may be the most straight forward to answer, because the set goals are published in many documents from the European Commission. The EU has defined three phases in which the transition to a hydrogen based world has to take place.

4.1.1 Phase 1: 2020 - 2024

Right now, we are in the middle of the first phase, which is from 2020 to 2024. The main goal in the first phase is to decarbonize existing hydrogen production. As mentioned in the *Introduction*, 96% of produced hydrogen in 2015 originated from fossil fuels. This will be done by installing at leat 6 GW of renewable hydrogen electrolysers in the EU. These electrolysers are ought to produce up to 1 million tonnes of renewable hydrogen.

In the first phase the manufacturing and development of electrolysers needs to be scaled up. In the ideal case the electrolysers would be powered directly from local renewable electricity sources. Different forms of carbon friendly hydrogen, especially those with near to zero carbon emission, like electricity-based hydrogen from solar or wind energy, will be most prominent in scaling up the production and the economy for hydrogen. Some already existing hydrogen production plants will need to be decarbonized by using carbon capture and other carbon storage technologies. Carbon capture and storage technology is capable of capturing and storing up to 90% of CO_2 that would otherwise be emitted into the atmosphere, preventing it from polluting the environment and contributing to global warming. [28]

4.1.2 Phase 2: 2025 - 2030

In the second phase, which runs from 2025 to 2030, the main objective is to make hydrogen an intrinsic part of an integrated energy system. The goal is to install at least 40 GW of renewable hydrogen electrolysers by 2030, which can realize the production of 10 million tonnes of renewable hydrogen in the EU. Renewable hydrogen is expected to become cost-competitive with other forms of hydrogen in this phase. Despite that, policies are still needed for industrial demand to include new applications and methods for a variety of industrial processes like the production of steel and transportation methods over land and sea. These policies to help renewable hydrogen compete and a general cost comparison between different kinds of hydrogen and fossil fuels will be further elaborated on in the Sub-question 3.

Renewable hydrogen will be used in balancing a renewable based electricity system by using abundant green electricity to electrolyse water and produce hydrogen. When the demand for energy is high, the hydrogen can be used to produce electricity again. This way hydrogen can be used for daily or seasonal storage, ensuring security and flexibility of energy supply. In the first phase some of the already existing fossil-based hydrogen production plants have to be decarbonized. This process of decarbonisation by retrofitting those hydrogen production plats using carbon capture has to be continued to further reduce greenhouse gas emissions and make the produced hydrogen more and more carbon-friendly.

4.1.3 Phase 3: 2030 - 2050

The third phase runs from 2030 to 2050. The goal in this phase is for hydrogen to be deployed at large scale to reach all hard to decarbonize sectors, like industry, where the production of cement, steel and chemicals are hard to decarbonize because of the need of for instance very high temperatures. In this phase renewable energy production needs to be heavily increased since the EU predicts that a quarter of all produced energy might be used for hydrogen production. Because of this hydrogen and hydrogen-derived fuels could be applied in a very wide range of sectors, from aviation to shipping, from industry to the heating of buildings.

[1]The entire of section 5.1 is written based on reference [1].

4.2 Sub-question 2: How is the EU planning to produce the intended amounts of hydrogen?

Hydrogen can be produced in several ways. Some ways are more carbon-friendly than others, but adjustments like carbon capture can be made to even make the the less carbon-friendly methods close to carbon neutral. To answers the second sub-question properly a general overview of different hydrogen production methods is given.

Hydrogen can be produced from natural gas in a process called natural gas reforming. Since natural gas mostly consists out of methane and high-temperature steam is used, this process is also referred to as steam methane reforming (SMR). 95% of hydrogen produced in the US (in 2016)[8] and 48% of hydrogen produced globally (in 2015)[7] was produced this way. SMR has a low efficiency since one third of the used natural gas is used to supply the high heat requirements for the process [9]. Furthermore CO_2 is emitted during the process, which can be counteracted by carbon capture, but since fossil fuels are used the process can be regarded as nonrenewable.

Gasification is a process in which coal and biomass is used to produce hydrogen in a series of chemical reactions, without combustion. With carbon capture and storage, hydrogen can be produced directly from coal with near-zero greenhouse gas emissions. Since growing biomass consumes carbon dioxide from the atmosphere, producing hydrogen through biomass gasification results in near-zero net greenhouse gas emissions without carbon capture and storage [8]. This is why gasification of biomass can be a great alternative for future decarbonized applications, which are based on renewable and carbon-dioxide-neutral produced hydrogen [10].

Another way hydrogen can be produced is by electrolisys. In this process electricity is used to split water molecules into hydrogen and oxygen. The origin of the electrical power is crucial in the carbon-friendlyness of the production process. Because of this renewable electricity is preferred to minimize carbon emissions. Electrolysis plants build in 2017 were able to reach efficiencies of about 80%. Meaning that the energy value of the hydrogen produced is about 80% of the electricity used to split the water molecule [11]. Because of the high efficiency electrolysis is also has great potential for energy storage.

Photoelectrochemical (PEC) hydrogen production is the process in which water is split into oxygen and hydrogen using (sun)light and special types of semi conductors. This process seems ideal, since it would skip a step compared to electrolysis, where first electrical power has to be generated after which the power can be used to split water molecules. Despite that photoelectrochemical processes have low efficiencies to this day, because of high electron-hole recombination. Nevertheless it might be a great hydrogen production method in the future [12].

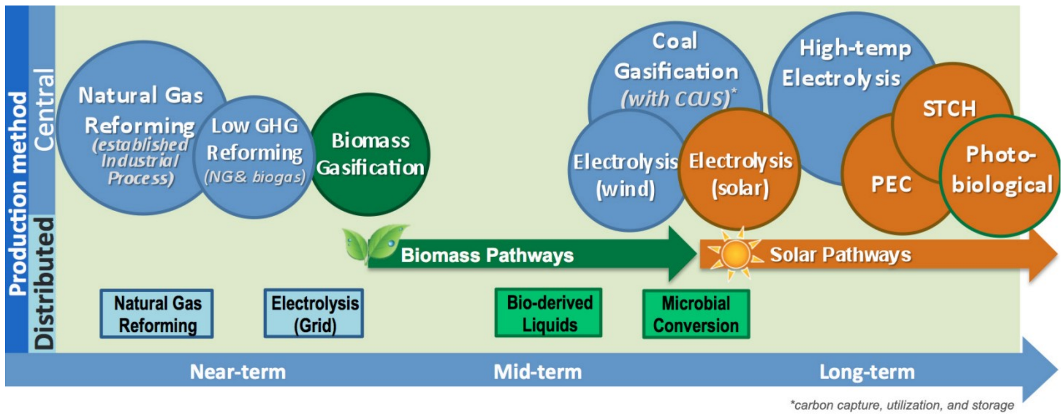


Figure 3: Different hydrogen production methods from near- to long-term. Taken from reference [8].

Renewable hydrogen is the focus of the European long term strategy, as it has the biggest decarbonisation potential and is therefore the most compatible option with the EU's climate neutrality goal [13]. Renewable hydrogen is defined as follows by the European Commission:

> 'Renewable hydrogen' is hydrogen produced through the electrolysis of water (in an electrolyser, powered by electricity), and with the electricity stemming from renewable sources. The full life-cycle greenhouse gas emissions of the production of renewable hydrogen are close to zero. Renewable hydrogen may also be produced through the reforming of biogas (instead of natural gas) or biochemical conversion of biomass, if in compliance with sustainability requirements.[13]

Despite the long term focus on renewable hydrogen, the EU strategy also acknowledges the fact that nonrenewable hydrogen with relatively low carbon emissions are indispensable to clean up existing hydrogen production and to scale up the market for the short term.

In the first two phases that were mentioned section 5.1, hydrogen production will still be mainly produced close to the user and close to renewable energy sources using electrolysers. Therefore it is necessary that renewable energy can be produced locally and that enough electrolysers are built. The EU has divided it's land in 109 NUTS2 regions. It is relevant to review if these regions have the potential to produce enough renewable energy to cover their own electricity demand and demand for electrolysis.

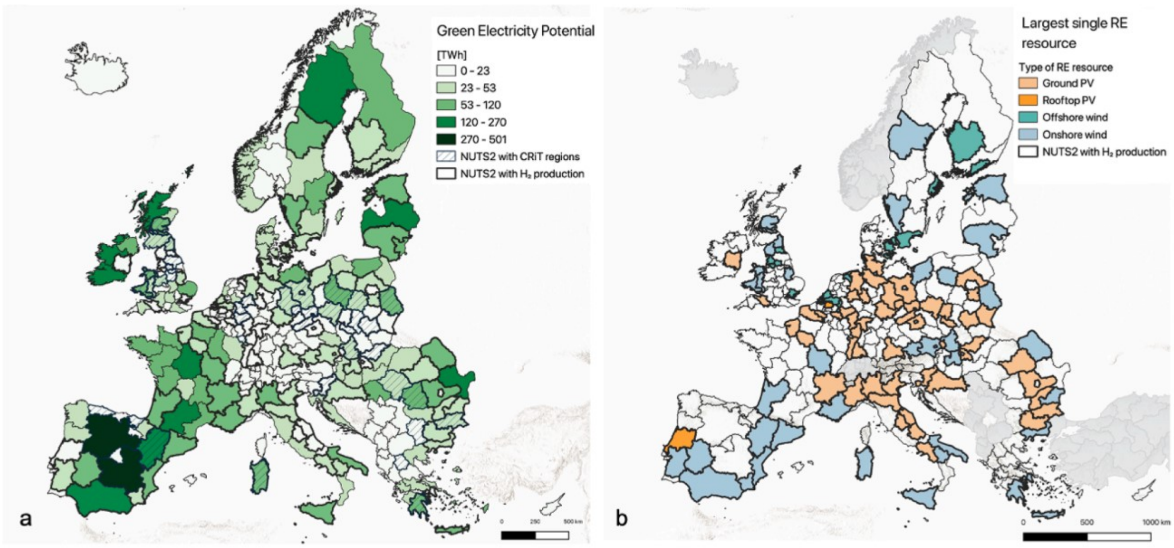


Figure 4: Panel a shows the total technical potential for green electricity per NUTS2 region, panel b show the single largest resource in that region. Taken from ref [14].

Notably, 84 regions have over 50% excess renewable electricity potential after covering the total electricity demand and that for water electrolysis. The majority of countries have a surplus of renewable energy potential. Meaning that enough energy could be generated easily in the EU and the European Union can be independent of neighbouring countries when it comes to energy. This is confirmed by the following diagram, showing energy demand, including demand for hydrogen production. The differences between renewable electricity potential and demand are remarkably big.

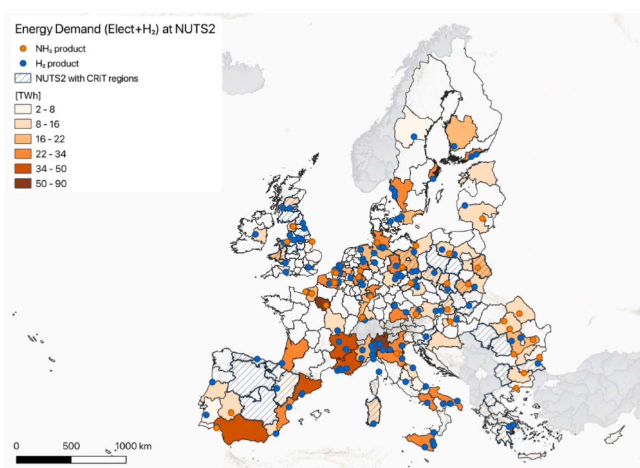


Figure 5: Energy demand including demand for hydrogen production per NUTS2 region. Taken from reference [14].

Partially for this reason 96 NUTS2 regions have sufficient solar, hydro and wind resources to cover all current electricity consumption as well as to substitute shift all grey hydrogen to green hydrogen. 88% of currently produced hydrogen is accounted for by these 96 regions. 76 regions have sufficient resources to fully decarbonize both energy consumption and hydrogen production [14].

Achieving the set EU goals that were elaborated on in section 5.1 requires a strong investment and subsidizing agenda. Investments in electrolysers can range from 24 to 42 billion euros in this decade. In the same period 220-340 billion euros are needed to scale up and connect 80-120 GW of solar and wind power to electrolysers to provide the necessary power. About 11 billion euros are needed to retrofit half of the already existing hydrogen production plants with carbon capture to further reduce carbon emissions. In addition to that approximately 65 billion euros are needed for logistics and infrastructure, like transport, storage, distribution and refuelling stations, based on an ambitious scenario of 665 TWh by 2030 [18][1]. From 2020 to 2050 the needed investments in hydrogen production plants is estimated to range from 180 to 470 billion euros in the EU [17]. Also hydrogen users, ranging from households to industry would need to adapt to be able to use hydrogen, for which also investments need to be made.

To support these investments and to make the transition from a fossil-based to a green hydrogen based energy EU the European Clean Hydrogen Alliance is established. The ECHA is open to all public and private actors that related to green or low carbon hydrogen that are willing to actively contribute to the goals set out by the alliance and almost 1000 companies and organisations are have joined the ECHA so far [19].

To make the transition and to build up a big scale hydrogen economy requires a full value chain approach. Meaning that every step in the process, from renewable energy production to produce hydrogen to creating market demand and everything in between, needs to be scaled properly and at the same time. When the creation of market demand grows with the supply, a virtuous circle of growing supply and demand is obtained in the ideal case. Reduced cost of green hydrogen production is essential in this stadium for green hydrogen to be able to compete with fossil fuels.

4.3 Sub-question 3: How is the EU planning to make hydrogen compete with carbon-based energy?

To realize the set EU hydrogen production goals and scale the hydrogen production and economy big investments are necessary. Furthermore green hydrogen has to be cost compatible with carbon-based fuels, to ensure a rise in demand. The cost compatibility of green hydrogen can be improved by subsidies, investments and legislation. That said, green hydrogen is already competing with grey hydrogen in some parts of Europe, the Middle east and Africa due to rising natural gas prices[15]. The rise in natural gas price was accelerated due to the Russian invasion of Urkaine.

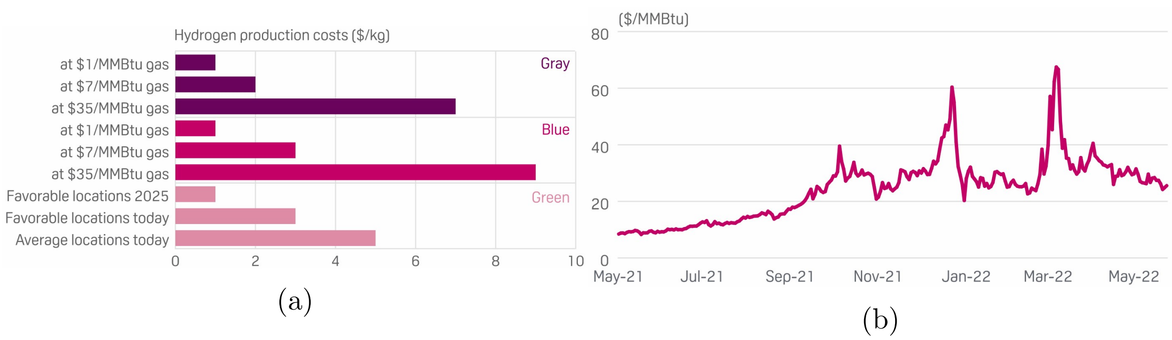
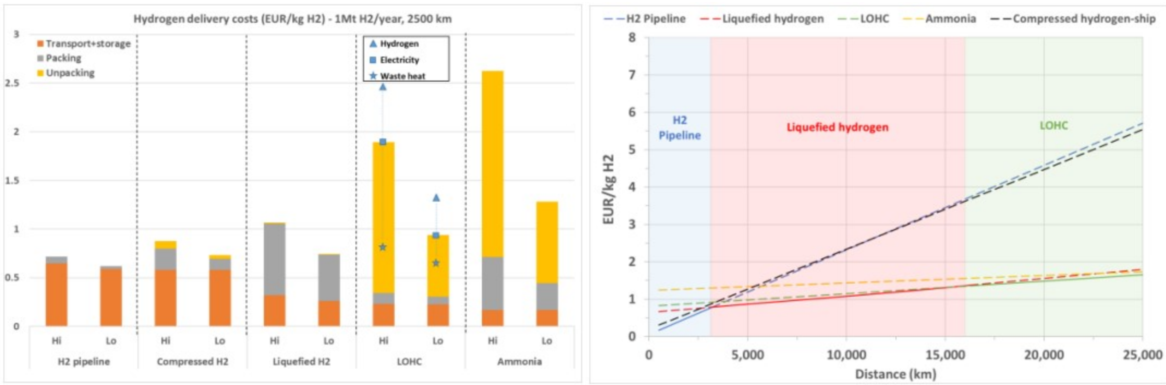


Figure 6: Panel a: Impact of increasing gas prices on hydrogen production cost. Panel b: Dutch TTF gas price in USD per Metric Million British thermal unit (MMBtu). Both diagrams taken from reference: [16].

In average locations in the EU currently, green hydrogen could be produced at $5/kg, below the $7/kg cost of gray hydrogen production with gas prices at $35/MMBtu, the ETC said in a report published in May 2022. Gas prices in Europe have remained above $20/MMBtu since the start of 2022, averaging more than $30/MMBtu, SP Global data showed. [16] All this is very fortunate for the green hydrogen market since naturally the demand for green hydrogen will grow because of its cost compatibility. Please note that these are only production costs and that distribution and transportation costs are not taken into account in figure 6.



(a) (b)

Figure 7: Panel a: Hydrogen delivery costs, Hi and Lo electricity prices for each carrier. Panel b: Hydrogen delivery costs for a simple (point to point) transport route, for 1 Mt of Hydrogen and low electricity cost scenario. Both diagrams taken from ref. [20].

When taking distribution costs into account, fossil fuels are still cheaper than green and grey hydrogen, also in the cheapest scenarios, making them more attractive for industry and many other applications in the short term. Action must be taken to turn the economy in favour of green hydrogen.

4.3.1 HyDeal Ambition

Scaling up green energy and green hydrogen production is one of the most straight forward solutions to make green hydrogen cheaper and cost compatible to fossil fuels, and exactly this is what the HyDeal Ambitions try to do.

The HyDeal Ambition is a group consisting of 30 European energy players that are planning to deliver solar-based green hydrogen at a price of €1.50 per kilogramme before 2030. The envisaged price of the HyDeal Ambition already includes transmission and storage of hydrogen. The group tragets to produce 95GW of solar energy and a achieve total of 67GW of electrolise power before 2030, more than the set goals by the European Commission![1]. This way 3.6 million tonnes of green hydrogen can be produced and delivered to consumers in the energy, industry and mobility sectors via the gas transmission and storage network every year [22].

HyDeal España is a project that spans Spain, France and Germany, and is the first part of the 67GW HyDeal Ambition project. HyDeal España will use 9.5GW of solar energy to power 7.4GW of electrolysers. The annually produced 330.000 tons of hydrogen will be supplied to a new industrial hub in northern Spain, and bought by ArcelorMittal and Fertiberia [21]. Other companies may join. By ensuring guaranteed off-takers, the hydrogen economy can grow faster, so it is essential to arrange agreements between hydrogen producers and consuments to scale up the hydorgen market.

Norwegian green hydrogen producer Nel even plans on producing green hydrogen for €1.50 per kilogramme in 2025, using a 2GW factory, being able to cut the hydrogen production cost by 75% [23].

An important thing to mention is that 70-80% of the price of green hydrogen depends on the price of green energy[23]. This means that to ensure cost compatibility to fossil fuels, more is needed than just scaling up.

4.3.2 Subsidies, legislation and taxes

To make hydrogen compete more with carbon-based energy a strategy is to make carbon-based energy less attractive for consumers using for instance taxes. This way energy consumers are forced to emit less CO_2 and to look for other solutions, like green hydrogen. In 1990, Finland was the world's first country to introduce a carbon tax. Since then, 18 European countries have followed, implementing carbon taxes that range from less than €1 per metric ton of carbon emissions in Poland and Ukraine to more than €100 in Sweden [24].

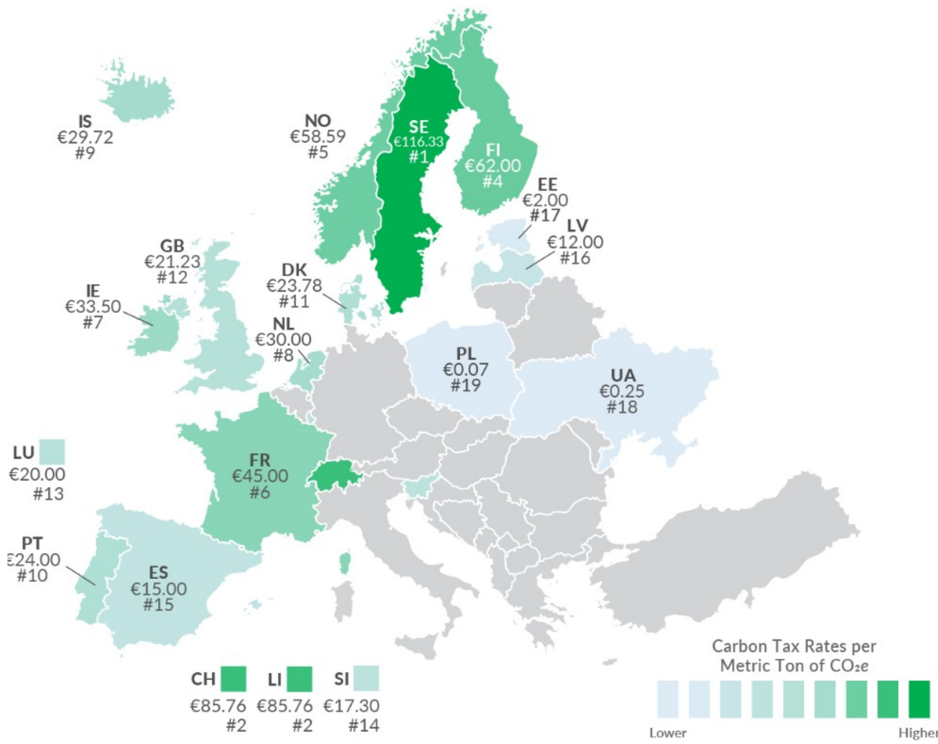


Figure 8: Carbon tax rate per metric ton of CO_2, as of April 1, 2021. Taken from reference [24].

Furthermore a lot of subsidy plans are proposed regarding green hydrogen and reducing carbon emissions. The Carbon Contracts for Difference, part of the REPowerEU scheme, are a funding mechanism that offer governments the opportunity to guarantee investors a fixed price that rewards CO2 emission reductions above the current price levels in the EU Emissions Trading System [25]. The REPowerEU Plan is a response to the abrupt market change due to the Russian invasion of Urkaine. Using this plan the EU wants to be independent of Russian natural gas and oil, by heavily investing in renewable energy and green hydrogen. Plans are for instance to double solar photovoltaic capacity by 2025 and install 600GW of solar power by 2030 [25].

Also plans regarding electrolyser firms have been announced. The so called Joint Declaration on Electrolyser Production is an agreement between the European Commission and 20 manufacturers that intends to make the production of 10 million tons of hydrogen per year possible by 2030 [26].

All these plans will partly be funded by the Recovery and Resilience Facility, that was originally intended for economic recovery after the COVID pandemic [27]. Because all of the plans are still in development concrete subsidies and founding plans are not yet available but will be in the next couple of months/years.

At the moment there are no concrete subsidies for private residents, partly because there is hardly any green hydrogen available, in addition, in order to produce green hydrogen on a commercial scale, industrial applications will first be looked at, after which subsidies for private residents will be looked into.

4.4 Sub-question 4: Is the transition from carbon-based energy to green-hydrogen based energy fast enough?

All the previously mentioned investment plans, development of new technologies, subsidies and taxes share a common goal: Get rid of fossil fuels and heavily reduce carbon emissions, to stop global warming. A fair question to ask is if all these new developments are enough to keep the average temperature within bounds. An average increase of 4 degrees Celsius is regarded as catastrophic, leading to more extreme weather and massive displacements of populations because of unbearable heat. Even when the earth warms up 'only' 3 degrees 30% of the world population will live in insufferable heats with average temperatures of 29 degrees Celsius and above, leading to mass climate refugee flows [29].

The name 'Global warming' already suggests that this problem affects the whole globe and needs a global approach. Therefore for answering this sub-question it is necessary to look beyond the borders of the European Union, and look at the global plans and agreements that were made. This question will not be necessarily about the implementation of green hydrogen, since that is only analyzed for the EU in this thesis and green hydrogen is only a component of the global energy transition and carbon emission plans that are being made.

4.4.1 Paris Agreement

The Paris Agreement is an international treaty on climate change, signed by 196 countries in 2015. Its goal is to limit global warming to well below 2°C, and preferably to below 1.5°C [30]. This will be aimed to do by reaching a carbon neutral world in 2050. At the time, this seemed enough to cap global warming at 2 °C, but new data suggests that the Paris Agreement is not enough. A report published by the United Nations Environment Programme has found that with current policies, the planet will warm 2.5-2.9°C [31]. The report analyzes the difference between where emissions are projected to be in 2030, and where they should be to minimize the worst climate change impacts.

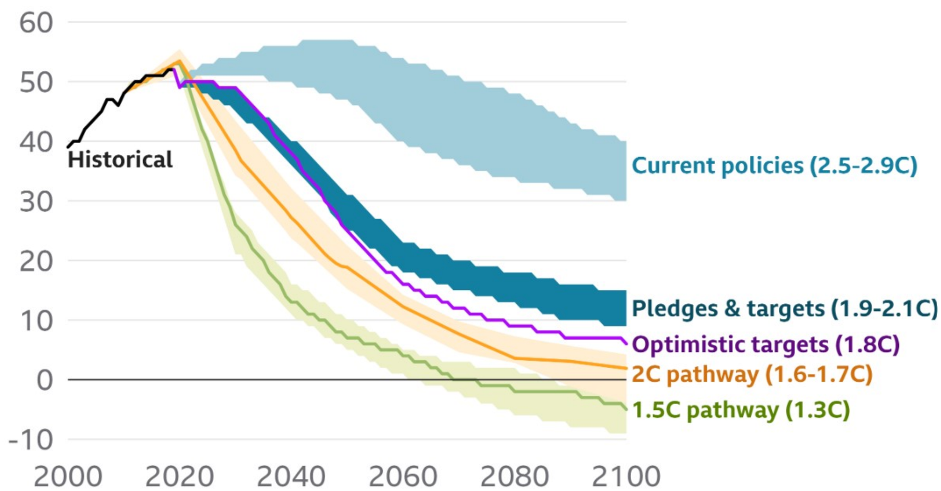


Figure 9: Past and projected emissions of CO_2 in Giga tonnes and their consequences. Taken from ref [32].

4.4.2 Lack of action

Reaching net zero emissions is done by reducing carbon emission as much as possible, and compensating the carbon that is emitted by planting trees, which removes CO_2 from the atmosphere. More than 140 governments have promised to reach net zero, covering 90% of global emissions [32]. However there is a problem, an analysis of Climate Action Tracker found that there is a big difference between the current policies in action and the arranged targets and pledges. Only a hand full of countries has concrete plans to reach the set goals.

Bill Hare, chief executive of Climate Analytics, one of the groups behind Climate Action Tracker put it in the following words:

> ”If they have no plans as to how to get there, and their 2030 targets are as low as so many of them are, then frankly, these net zero targets are just lip service to real climate action.”

This says little good about the current state of affairs. This is also confirmed by Intergovernmental Panel on Climate Change, one of the leading scientific organisations on climate change, in a devastating report released this year [33]. At the presentation of the report United Nations Secretary General António Guterres called the report “litany of broken climate promises” and a “file of shame” [34].

The report shows it is still possible to keep global warming below 1.5°C, with fast implementation of massive emissions cuts across all sectors. Government commitments to reduce emissions are not high enough to realize this. The report also makes clear that we have the resources to achieve emission reductions and make the transition from fossil fuels to renewables. But all these measures require action, concrete plans and political will, which is lacking.

4.5 Research question: How is the EU planning to reach the set hydrogen production goals in the next decades?

Now that a proper framework is established by answering the sub-questions, the research question can be addressed. The answer of the research question will predominantly consist of parts already achieved by analyzing the sub-questions.

The process of reaching the set hydrogen production goals of the EU is a complex and very integrated objective that includes many different sectors. To keep a good overview, three different phases are established, to have some anchor points in time. Phase 1 runs from 2020-2024, phase 2 from 2025-2030 and phase 3 from 2030-2050. When certain goals are set per phase a feel of urgency is more prominent since deadlines are not so far away in time.

Phase	Electrolyse power (GW)	Annual hydrogen production (in million tonnes)
1	6	1
2	40	10
3	-	-

The European Commission published a report presenting their hydrogen strategy for a climate neutral Europe in 2020. The concrete goals per phase can be seen in the table above. A dash, meaning that no precise number was found in the report. More recent publications of the European Commission presented more ambitious goals, as a part of the REPowerEU plan, to become independent of Russian fossil fuels.

A full value chain approach in combination with a strict agenda is needed to reach the set ambitions. Meaning that every step in the whole process has to be stepped up gradually at the same time for the economy to grow on itself.

Electrolysis, using renewable energy, will be the main way of producing hydrogen in the future in the EU. Nowadays the vast majority of produced hydrogen is made from fossil fuels, but by investing solar and wind energy and building electrolysers green hydrogen can be produced. To support the massive subsidies the European Commission will help to overcome the main obstacles preventing rapid electrolyser growth. The main obstacles are lack of concrete regulatory frameworks and subsidies for large-scale green hydrogen production, the fact that there is no guaranteed renewable hydrogen demand and the challenges of being able to obtain the right amounts of raw materials for electrolyser development[26].

Renewable energy sources will need to be scaled up drastically, because the production of 10 million tons of green hydrogen will require about 290-500TWh of renewable electricity, adding to already high demand resulting from electrification and the decarbonisation of many already existing technologies [35][14]. To put this in context more than 10.000TWh of energy is consumed each year in the EU [3], from which 45% is aimed to be renewable in 2030 [38]. This percentage initially was lower, but was announced as part of the REPowerEU scheme to accelerate independence from Russia.

Many plans are announced to accomplish these high renewable energy demands. One of which is the HyDeal Ambition, which is a collaborative of 30 prominent energy players, strategic consultants, engineering firms, legal firms, investment banks and digital firms [36]. A very diverse interdisciplinary team of experts which is essential to the complex full value chain approach that is needed. The HyDeal Ambition was announced in February of 2021 and the goal is to produce 95GW of solar energy and 67GW of electrolyse power by 2030. The first project of the HyDeal Ambition has already started in Spain, and will expand into France and Germany. After this other projects will be started in Italy, Central-Europa and North-Africa [37].

The REPowerEU plan is a plan to decrease dependence of Russian fossil fuels. Ending this reliance will require a massive scale up of renewables and faster electrification and decarbonisation of fossil intense industries. The plans and goals published by the European Commission in 2020 (40% renewables) are outbid by the more recent announced goals (45% renewables)[38] and the European energy transition is accelerated. This offers great opportunities for the hydrogen economy.

For hydrogen to be able to play a prominent role in this accelerated transition, plans have to be made to ensure enough electrolyse capacity and enough demand for green hydrogen. The Joint Declaration of Electrolyser Production aims to increase their manufacturing capacity tenfold to 17.5 GW per year[39]. The Declaration also features actions of the European Commission to support a regulatory framework, facilitate access to finance and ensure efficient supply chains. Furthermore the EIB is willing to support and fund hydrogen projects. Already 550 million euros of funds were provided and 1 billion euros of funds are under consideration right now [40].

To further encourage decarbonisation and green hydrogen implementation, the Carbon Contracts for Difference, part of the REPowerEU scheme, is introduced. The CCfD is a funding mechanism that rewards carbon emission reductions, by ensuring a fixed carbon price. This gives security, because it minimizes price uncertainty, which makes investing in the unpredictable carbon market more appealing.

Cost compatibility will be one of the most important components for the green hydrogen market to grow on itself. Without cost compatibility, there will be almost no economic drive for companies and industries to make the transition from fossil to renewable. Compatibility of cost can be done by making fossil fuels more expensive or implementing a carbon tax, or by making green hydrogen cheaper. Carbon taxes are already implemented in 18 EU countries and cheaper green hydrogen will be primarily realized by scaling up, by for instance the HyDeal Ambitions.

Many goals are set by the European Union, but action has to be taken. Not only for green hydrogen production and implementation, but for the energy transition as a whole. The policies and actions currently in place are not enough to meet the EU's emissions reduction target of "at least 55%" by 2030 below 1990 levels. Despite that, the European Commission is currently considering an discussing a number of policies, plans and funds to be implemented in the near future. If those policies and plans will be adopted and implemented on time by the Member States, the ambitioned emmission reduction goals of 55% could even be overachieved[41].

5 Discussion

The transition from fossil-based energy to green hydrogen based energy is a complex process that spans almost all sectors. Therefore it is almost impossible to address all relevant topics within this transition. In addition to that, many plans and actions are currently under consideration, in combination with the Russian invasion of Ukraine, making this subject very dynamic. Some aspects even are uncertain and unpredictable in the future, like the influence of the current crisis with Russia on fossil fuel prices.

In this thesis the emphasis primarily lies on how the European Union envisions to realize the set hydrogen production goals, by scaling up renewable energy production, scaling up and building new electrolysers and ensuring green hydrogen demand and cost compatibility to fossil fuels. As already mentioned the transition demands a full value chain approach, meaning that some relevant parts in the transition were only briefly mentioned or not elaborated on fully. Aspects that would be interesting to look into further are discussed shortly in the next paragraphs.

Infrastructure is a major component of the transition. Ensuring the possibility to transport enough green energy to electrolysers and distributing the hydrogen efficiently is crucial to a good transition. Pipelines may be needed for long distance transport, local transport may be possible via trucks with highly compressed hydrogen. Local refueling stations for cars need to be build and supplied with hydrogen and when green hydrogen will be used to replace natural gas at home this comes with its challenges. Some argue that underground gas pipes that are currently used for natural gas can be converted to hydrogen gas pipes in the future. This is just the tip of the iceberg of the infrastructure component of this transition, which might be very interesting and relevant for a follow up study. Furthermore it might be very wise to investigate in which areas hydrogen really excels over electricity. In many cases just using green electricity is much more convenient and efficient than using green hydrogen. This is because the hydrogen does not have to be produced (and burned) in the first place, making it more efficient, and a lot of infrastructure regarding electricity is already in place, opposed to hydrogen infrastructure which is lacking at the moment.

The crisis with Russia and the Russian invasion of Ukraine has big influence on the price of fossil fuels in Europe, since Europe imports vast amounts of oil and natural gas from Russia. Further developments regarding the relation between European countries and Russia and further economical sanctions are hard to predict in ahead of time. Because of this, natural gas prices are uncertain and fluctuating. At the moment this research was executed, natural gas prices are more than 3 times that of what they were a year ago. The price of natural gas has very big influence on the cost compatibility of green hydrogen vs. grey hydrogen and fossil fuel in general. Anticipating correctly to the fluctuating fossil fuel market is crucial for the green hydrogen economy to use the rising natural gas price as an opportunity. Therefore doing research into and trying to predict further development might be useful to do.

Another question that might be worth looking into and that is not discussed in this thesis is about the definition of 'green/renewable hydrogen'. Since the European Commission defines it as hydrogen that is produced by electrolysis using renewable energy. But what if a massive electrolyser plant is built, which uses almost all of the renewable energy production of a region, and because of that more fossil fuels have to be burnt to make up for the increase in overall electricity demand. More carbon is emitted because of the production of 'green' hydrogen, making it possible to argue that this hydrogen is not green after all. The definition of green hydrogen might need revision.

Carbon capture was briefly mentioned as a solution to 'clean up' non carbon friendly hydrogen production methods or other carbon emitting processes in general. Carbon capture has always been a controversial topic. It is indispensable to achieve negative emissions, but opponents argue that 'wrong' implementation can stall decarbonisation of many processes. Further inspection on the role of implementation of carbon capture might be an interesting follow up study.

6 Conclusion

The EU has set the goal to reduce CO_2 emissions by 90% below 1990 emission levels. This will be carried out by heavily investing in more renewables and decarbonisation of heavy emitting sectors. The use of hydrogen is indispensable in this transition. Hydrogen can be used as an energy carrier, to store or transport energy and hydrogen can be used in hard to decarbonize sectors, that cannot be decarbonized using green electrical power. A full value chain approach in combination with a strict agenda is needed to reach the set ambitions. Electrolysis will be the main way of producing green hydrogen. The HyDeal Ambitions, REPowerEU, CCfD and Fit for 55 are all recently announced plans to realize the transition from fossil-based energy to renewable based energy, using electricity and green hydrogen. Despite that, clear and concrete implementation of the plans seem to be lacking. This is partly because many concrete actions are still under consideration of the European Commission. That said, politicians and governments need to feel the urgency and act now, for the climate goals of 2030 and 2050 still to be achievable.

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