HYDROGEN FOR THE CERAMIC INDUSTRY

- FROM AN INFRA POINT OF VIEW -

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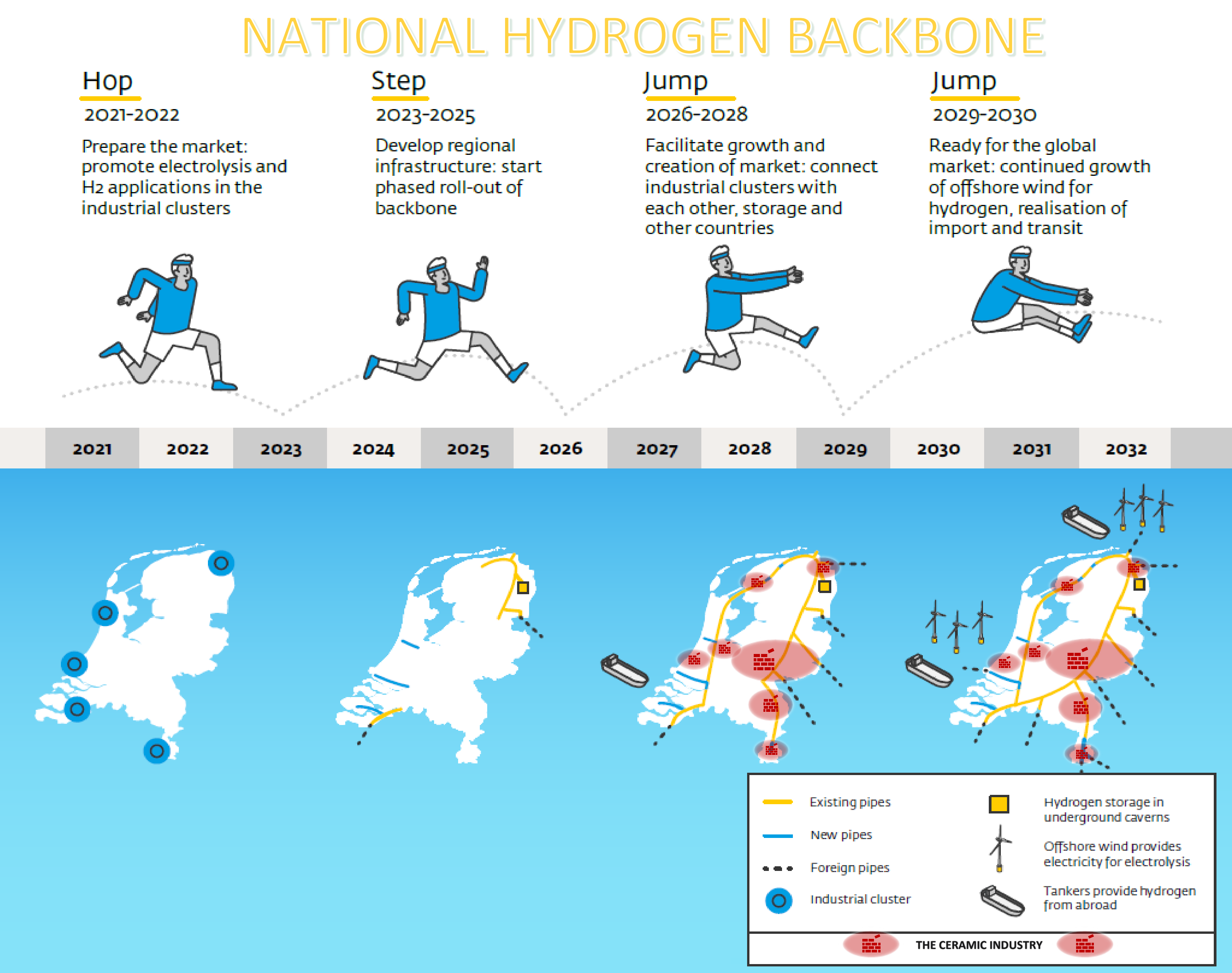

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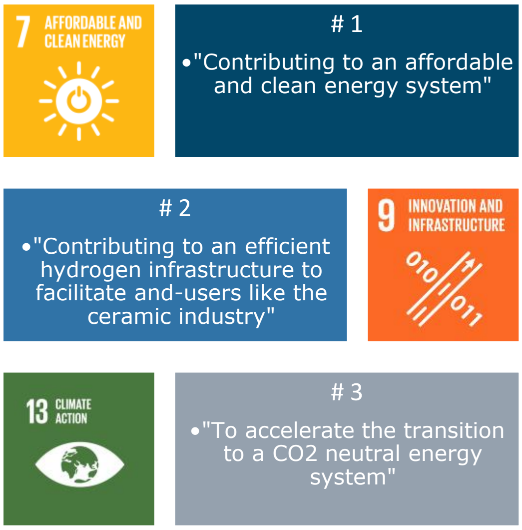
With great pleasure we present this report on a hydrogen outlook for the Dutch ceramic industry, from an infra perspective. As part of the eight-month Nudge education program we focused on creating an impact for the 2030 Paris climate agreement.

Why the 2030 climate agreement, hydrogen & the ceramic industry? Because we dream about living in a world where we do not feel guilt or shame about the footprint we leave behind. Through the support and supervision from the United Nations, world leaders and politicians, we strive to achieve the pictured Sustainable Development Goals (SDG's). This to create a future where a companies' market value is growing exponentially when they demonstrate a purposeful impact on the environment.



Working at Gasunie means we can contribute. This report is our effort to show an industry what is possible with green molecules like hydrogen. A bright future is ahead of us, which can only be reached if we work together across the sectors, share knowledge & experience and take necessary actions.

One thing we do know, is that we could not have established this report without the help of a lot of people. In special we want to thank our internal impact advisors: René Schutte, Helmie Botter & Marijke Kellner and all our colleagues that participated, for their input and feedback. Furthermore, we want to express our gratitude towards the Royal sector association for Dutch Ceramics, the directors of the ceramic industries, Netbeheer Nederland en Liander, who were helpful by sharing expert knowledge. They offered us valuable insight on the ceramic industry and regional distribution networks during this project.

Your sincerely,

Chantal, Cato & Anne-Marijn

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1. Vision and project definition

1.1 Dream of sustainability in the future

We dream about living in a world where we do not feel guilt or shame about the footprint we leave behind. In the future, we know what activities, consumptions and work practices are beneficial for the environment. Together with our generation, we feel the responsibility to eliminate the practices in society that are not aligned with this knowledge. There is a clear and shared commitment within the generation to help the world to heal from the past, which brings people closer together than ever before. Through the support and supervision from the United Nations, world leaders and politicians, we strive to achieve the Sustainable Development Goals (SDG's). This felt responsibility leaves a clear mark on the national and global economic and business environment. We see in the future that companies' market value is growing exponentially when they demonstrate a purposeful impact on human rights, community and society, and the environment. It is the norm that industries, households and institutions in The Netherlands are thriving from the use of green gas, green electricity, and hydrogen. The use of hydrogen as an energy carrier is paving its way to pass its' break-even point in the upcoming years. The revenues are passing the expenses due to the wide financial support from investors and businesses, which brings possibilities to innovate further. We will use a combination of central and decentral green energy systems and we are debating with other world leaders how to expand this integrated system globally. A bright future is ahead of us, which can only be reached by national and global collaboration in our generation. Together, we feel the responsibility, the willpower, and the confidence to act upon this chance to save our planet.

1.2 Vision of the Netherlands (2030) – Hydrogen

The Netherlands aims for a reliable, clean, affordable, safe and spatially correct energy system. Ministry of Economic Affairs and Climate Policy described the governments vision for Hydrogen. See for the highlights Figure 1. The message is clear: renewable hydrogen is a necessary chain in creating the above-described energy system. They therefore want to introduce a National Hydrogen Program and in the described timeline they present that they will start with the following initiatives (Eric Wiebes, 2020):

- Realising the first production facilities for hydrogen
- Creating a system for guarantees of origin.
- Acquiring experience with hydrogen in sectors.
- Starting research to investigate whether and under which conditions, the national infrastructure for natural gas can be converted to a national infrastructure for hydrogen.
    - This research is partly conducted by Gasunie. Insights of this research (HyWay 27) are incorporated in this report.

Figure 1 "Highlights governments vision for hydrogen" (HyWay27-projectteam, 2020)

1.3 Vision Gasunie (2030) – Hydrogen

Gasunie believes that hydrogen will play a major role as the energy carrier of the future. An important reason for this lies in the two fundaments of providing energy: 1: storing and 2: transporting it. The storage of hydrogen is thousand times cheaper than storing electricity, and transporting these molecules is twenty times cheaper than electrons (Visser, 2017). As an independent network company and connector, Gasunie will connect hydrogen from various suppliers and via the national hydrogen grid (hydrogen backbone) to end-users like the large industrial clusters in The Netherlands (see Figure 2). To achieve this, Gasunie is committed to accelerate a climate-neutral energy supply by developing infrastructure and storage facilities. This is the reason that Gasunie is investing in hydrogen projects and preparing the adjustment of the current natural gas infrastructure, to pave the way for hydrogen. This infrastructure should be ready for the usage of hydrogen by 2030.

The hydrogen infrastructure that Gasunie envisions carries a capacity of approximately 10-15 GW. To illustrate: 1 GW delivers 24GWh/day = 2.456.639 m^3/day = 896.673.235 m^3/year. So, 15 GW will result in 13.450.098.525,- m^3/year. Therefore, theoretically speaking, the envisioned hydrogen backbone can supply about 1921 ceramic companies (a ceramic company uses on average 7.000.000 m^3/year).

This national hydrogen infrastructure is called the: "Gasunie hydrogen backbone. Eventually it will entail a transport network that connects the five major Dutch industrial clusters and our seaports, storage and future German and Belgian hydrogen networks. Existing energy systems will get more integrated towards 2030. Hydrogen can play a key role to maintain balance in this integrated system as a sustainable alternative for natural gas that also delivers this function currently. Also, by converting excess electricity to hydrogen it is possible to store the energy in large amounts to, for example, account for the seasonal/daily fluctuations. Therefore, hydrogen gives the flexibility and reliability as it can be used any time, which enables a reliable overall energy system for the Netherlands.

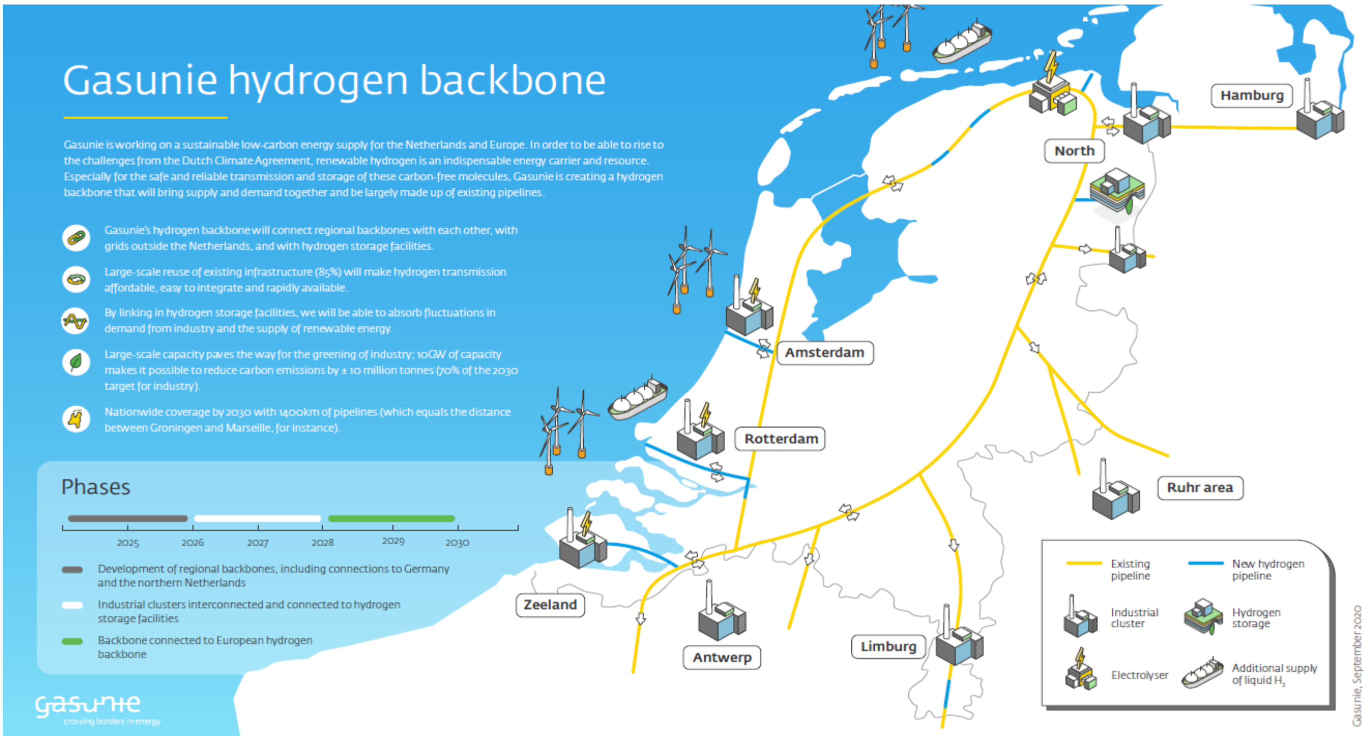


Figure 2 "The national hydrogen backbone"

1.4 Motivation for the project

In the Netherlands the climate goal is set to reduce 49% of the CO_2 footprint by 2030 (Klimaat Akkoord, 2020). The industries in the Netherlands are a big contributor to the high CO_2 emissions. Partly due to their use of fossil energy sources. The Ministry of Economic Affairs and Climate Policy of The Netherlands divided the industries in six clusters and asked for a plan to reach the CO_2 emission reduction goals. Five of these clusters are based on their geographical location. Unlike the first five clusters, the sixth cluster consists of nine divergent industries located all over the Netherlands. This leads to a personalized approach, which makes it more complex for this cluster to increase its' sustainable footprint. The complexity requires specialized attention in order to be on time with taking action towards the 49% CO_2 reduction goal.

As a team, consisting of three young and driven individuals, we would like to make an impact by stimulating the use of hydrogen as an energy carrier within the Netherlands. To do this, we are putting our dream into action. In our dream, we touched upon the clear role for hydrogen to reduce emissions and to have a sustainable impact on industries. Regarding cluster six, we see the possibility to use this impact plan as an opportunity to explore the options of a hydrogen (carbon free) infrastructure for this cluster. With this plan, we strive for decarbonizing the industry to contribute to counteracting the climate change problems that this industry faces.

1.5 Why focus on hydrogen and cluster 6?

The report of the Taskforce Infrastructure Climate agreement Industry (TIKI) states that we shall use molecules because there is not enough capacity in the electricity grid for all the industries (DNVGL, 2020). Currently, there are ongoing studies on how to connect the first five regionally centralized clusters to the national hydrogen backbone. In these studies, cluster six is not included due to dispersed character of the industries within this cluster. However, when looking closer at cluster six, there are feasible possibilities for industries to connect to the hydrogen backbone.

1.6 Why focus on hydrogen and the ceramic industry within cluster 6?

Within the sixth cluster there are multiple industries. One of the industries clustered in the region Gelderland is the ceramic industry. This industry has a long history with the use of natural gas. Molecules in comparison with electricity can create higher temperatures which are needed for the firing process within this industry. For the 2030 climate goals, this industry needs a sustainable alternative for natural gas. Based on the report of cluster 6 (DNVGL, Taskforce Infrastructuur Klimaatakkoord Industrie - MIEK 0.1, 2020), we concluded that the ceramic industry could be a valuable industry for the 2030 planned hydrogen backbone. Our resoning behind selecting the ceramic industry is presented in Figure 3.

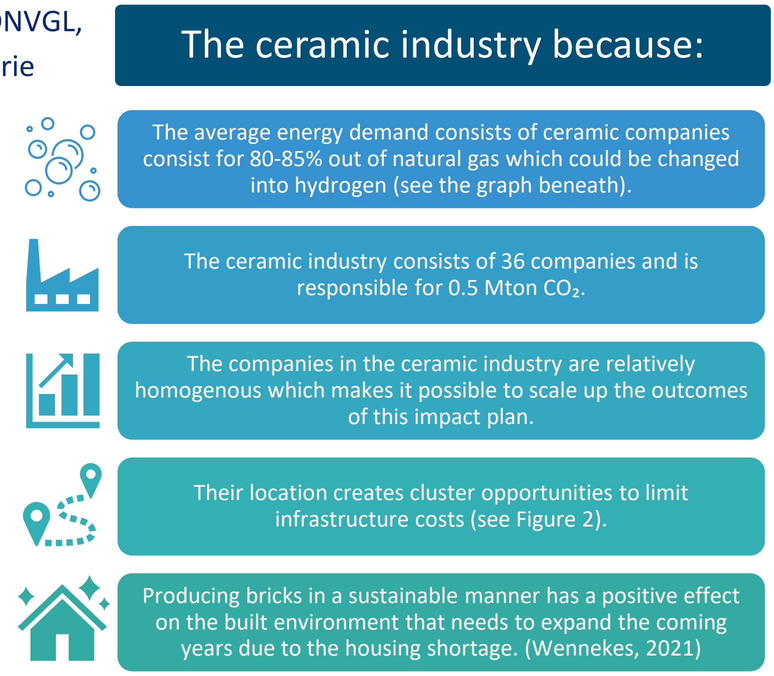


Figure 3 "Hydrogen for the ceramic industry because..."

In summary hydrogen has great potential for this industry, especially considering how depending the ceramic industry is on having sustainable molecules as a clean energy source, this dependency is also pictured in Figure 4 (expressed in PJ).

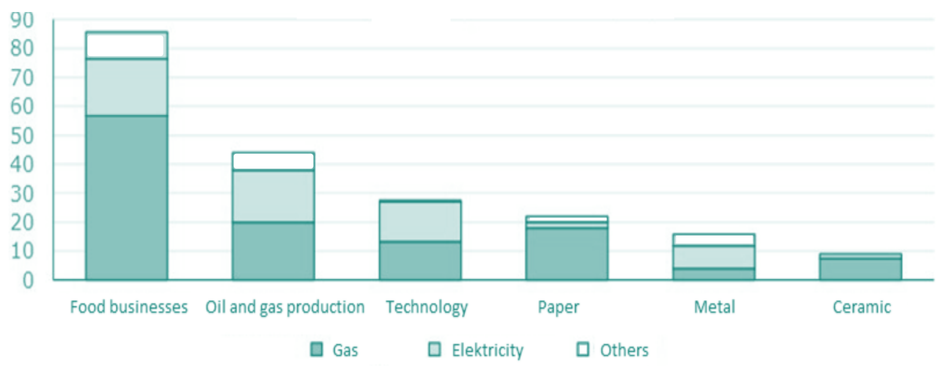


Figure 4 "Energy demand and structure within cluster 6 in PJ"

1.7 Scope of the project

The goal of this project is to provide insight for the ceramic industry on the development of the energy market in the short- and long-term future. This research can guide the industry in setting the first steps towards choosing a sustainable energy source. In addition, it highlights the uncertainties which still need to be researched. And it covers several recommendations towards both the industry as the government and infra-companies that need to be addressed to make the transition possible.

This report focusses on the current situation, hydrogen in combination with the ceramic industry, location of the hydrogen backbone; the ceramic companies and a financial analysis.

To write the rapport in the stated time the research presumed some conditions:

- There is a national hydrogen backbone by 2030
- There is enough blue/green hydrogen production for supplying the ceramic industry
- The project used standard indicators (public figures) to make forecast analysis

Furthermore, the scope of this research is defined by:

- Future price analysis for a ceramic company is forecasted till 2030
- This research solely considers applying hydrogen as a sustainable energy source. How for example green gas can function as primary energy source, is not included in the scope of this research
- The focus is on employing the National hydrogen backbone to supply the ceramic industry. Other means of transportation are out of scope.
- This research does include a first analysis in determining opportunities to deploy the regional network operators (new/existing) for a connecting the industry to the hydrogen backbone.

2. The bigger picture: a climate neutral EU (2030-2050)

In order to understand effect of the Paris climate agreement, this chapter outlines the policies and pathways to a sustainable climate and what this implies for 2030 as well as 2050 from a policy point of view. Both on national level as for the EU, policies are enacted. How this impacts the ceramic industry is explained in this chapter.

2.1 Effect of the Paris climate agreement for the ceramic sector

2.1.1 The long-term climate goal for 2050 is set

In December 2015 the Netherlands signed the Paris climate agreement. The increase of temperature on earth compared to the pre-industrial era should stay below the 2 degrees Celsius. In order to operationalize this goal, the Netherlands defined a National climate agreement in 2019. The law states that greenhouse gas emission should be 95% lower in 2050 compared to 1990. In addition, for 2030 the Netherlands has set a target of 49% CO_2 reduction. The EU also operationalized the Paris agreement by publishing the European Green Deal in December 2019. The EU Counsel thereafter decided on being climate neutral in 2050. For 2030 the EU has set a target of 40% CO_2 reduction (Deal, 2021).

2.1.2 The upcoming CO_2 reduction target for 2030 is increased

One year later (December 2020), the EU counsel presented the Climate Target Plan. This plan states that the reduction of greenhouse gases should be increased from 40% to 55%. The EU heads of government accepted this proposal in December 2020 (Deal, 2021).

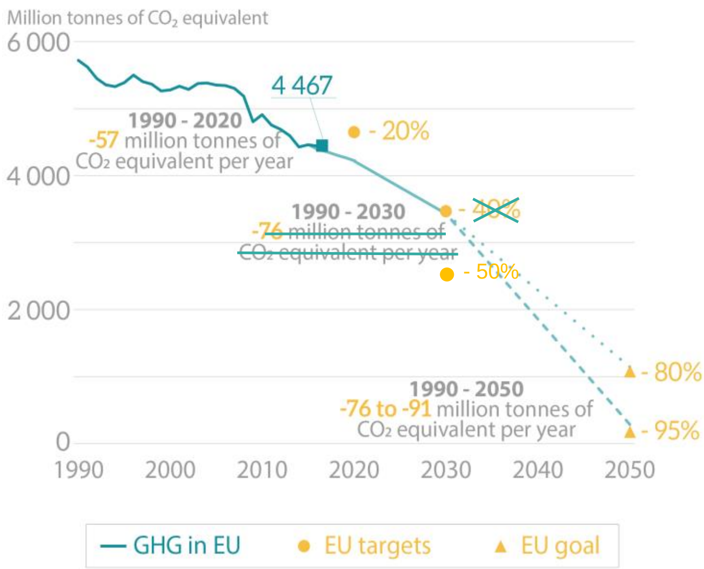


Figure 5 "Greenhouse gas emission trend projections and targets in the EU" (Agency, 2019)

2.1.3 The new 55% reduction target is probably going to result in stricter measurements but the effects for the Netherlands and industries is unknown

Commission Laura van Geest[1] analysed what the new 55% EU target implies for the National climate agreement and defines possible routes for the Dutch politics to base decisions on (Deal, 2021). Simply speaking, there are three options: the Netherlands can keep the current climate agreement and target of 49%; they can increase our target to EU level (55%), they can even set the target higher than EU level or they can stop with having a national target and stick with the EU target and instruments. What this means for energy intensive industries is shown in Figure 6. The European Commission presented in July 2021 the Fit-for-55 package. This aims to align climate, energy, land use, transport and taxes in such a way that the net emissions can be reduced by at least 55%. This brings new insights for every industry.

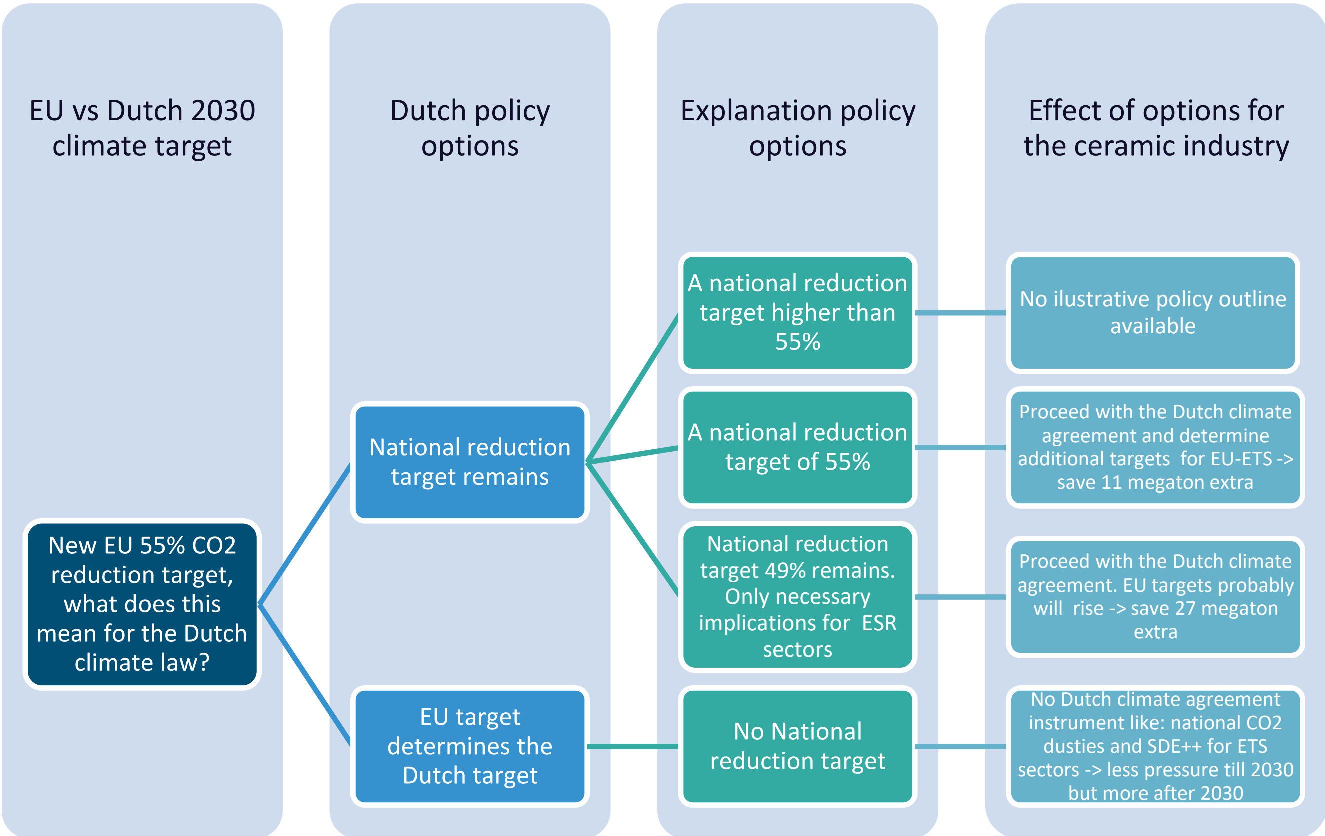


Figure 6 "EU and Dutch climate policy - policy routes for the Netherlands"

[1] *New steps are needed to raise the Netherlands' climate target of 49.55 percent less greenhouse gases by 2030. The report published by the official study led by Laura van Geest provided the fundamental insight for raising this target. The study was mainly intended for the new cabinet to be formed, after the elections of March 17, 2021. Link via: https://www.rijksoverheid.nl/documenten/rapporten/2021/01/29/bestemming-parijs-wegwijzer-voor-klimaatkeuzes-2030-2050*

2.2 The effect of National & EU climate agreement instruments for the ceramic industry

Unfortunately, on EU level the CO_2 reduction target per instrument is not clear yet (see paragraph 2.1) and therefore the Netherlands cannot determine yet what the best pathway is for the Dutch climate agreement instruments & targets.

The EU divided the reduction target (now 55%) in two subsequential steps:

- Step 1: targets are set on EU level for energy intensive industries: EU-ETS. This creates a certain CO_2 reduction rate. It also means that countries with a high number of energy intensive industries will contribute more.
- Step 2: the remaining CO_2 reduction effort on EU level is translated to national targets which are negotiated with the EU countries. For these targets two target groups are addressed:
    a. Non-ETS industries by means of the ESR arrangement (contains national targets for e.g., the built environment, mobility and smaller industries)
    b. Agriculture sector by means of the Lulucf arrangement (contains national targets for: land-use, land-use change and forestry)

Only until it is determined on EU level, what the shares will be of the above-described instruments in reaching the 55%, it will be clear what this means for the target in the Netherlands. EU negotiations regarding the ESR & Lulucf will start after this summer (2021). (Katrijn de Ronde, 2021).

2.2.1 What the EU-ETS system means for a ceramic company in the coming years

The ceramic industry is appointed as an energy intensive sector and therefore falls within the scope of EU Emissions Trading System (EU-ETS). This entails that those ceramic factories are obliged to pay a CO_2 tax. Actually, the tax is a: “cap-and-trade system in which governments set an allowable total amount of emissions (“cap”) over a certain period and issue tradable emission permits (“trade”). These permits, which are typically good for 1 ton of CO_2, are a currency in carbon markets” as Aklin describes (Aklin, 2020).

Because the cap of permits is lowered every year, permits will get more expensive. Considering the previous chapter (new EU target), extra measures will probably be taken. In financial light this implies that the costs per permit must rise. Shell analyzed to what extend the permits should rise and calculated that the costs should rise above the €200/ton CO_2 per 2030 to reach climate neutrality in 2050 (Hatherick, 2020). The current price for one ton of CO_2 is set at: €50,35 (Ember, 2021). A linear forecasted CO_2 price, based on these parameters is pictured in Figure 7. The influence of these forecasted costs for a ceramic factory is described in chapter 5.

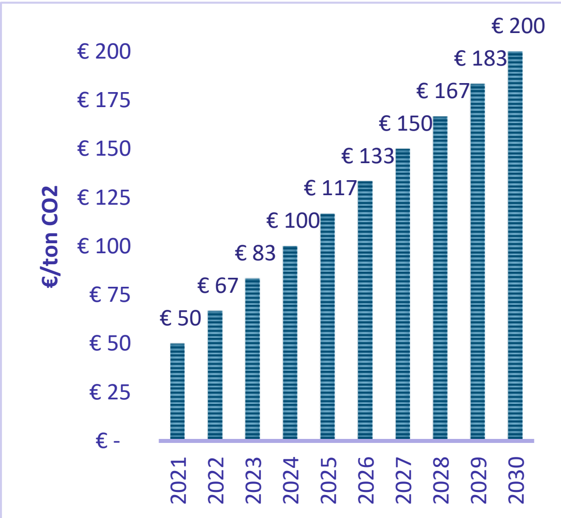


Figure 7 "Forecasted €/ton CO_2 EU-ETS, to reach climate neutrality by 2050"

2.2.2 What the Dutch CO_2 tax means for a ceramic factory in the coming years

With the Dutch climate agreement, the Netherlands decided to introduce a CO_2 tax on National level that operates parallel to the EU-ETS system. This Dutch system should help reaching a National target of an additional -14,3 Mton CO_2 by 2030 (on top of what was already agreed upon). The CO_2 tax started in January 2021.

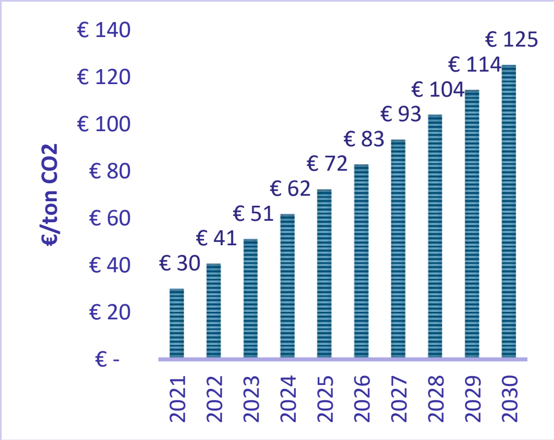


Figure 8 "Forecasted €/ton CO_2 Dutch tax in order to reach the additional -14,3 Mton CO_2 by 2030"

The Ministry of Economic Affairs and Climate Policy, explains that, as for the EU-ETS system, the Dutch CO_2 tax on avoidable CO_2-emissions (above a specific benchmark) will also be based on a ton CO_2. The price in 2021 is fixed at 30 euro and will rise every year with: €10,56 in order to reach a price of €125 per ton CO_2 in 2030. See Figure 8 "Forecasted €/ton CO_2 Dutch tax in order to reach the additional -14,3 Mton CO_2 by 2030" for the forecasted CO_2 price based on governmental policy. (EZK, 2020).

However, EU-ETS companies like the ceramic industry do not have to pay the full tariff. The tariff to pay for the Dutch tax is calculated by the following formula, see Figure 9.

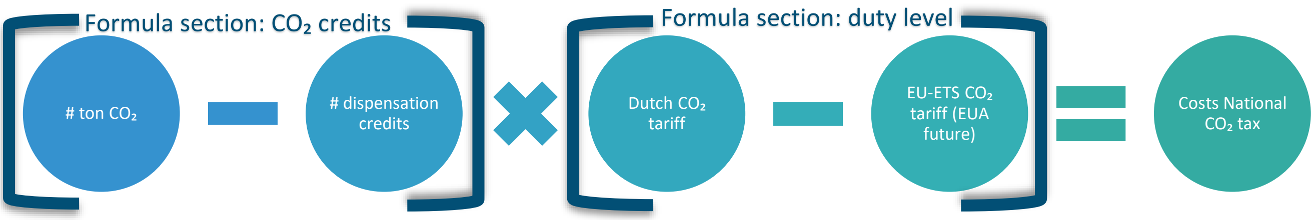


Figure 9 "Dutch CO_2 tax calculation method"

Applying the above-described formula can result in an outcome where no Dutch CO_2 tax has to be paid, this happens when:

- The amount of dispensation credits outset the CO_2 emissions of a ceramic company. The left part of the formula "CO_2 credits" will result in a negative number. This is not possible, so the outcome is 0. Multiplying 0 (CO_2 credits) with the formula section: "duty level" will result in: zero costs for the National CO_2 tax. It should be noted that dispensation credits cannot be saved for upcoming years and the max of dispensation credits will be lowered every year. The influence of these forecasted costs for a ceramic factory is described in chapter 5.
- The same formula principle also applies for the section: "duty level". When the Dutch CO_2 tariff per ton is lower than the EU-ETS CO_2 tariff for a certain year, formula section: "duty level" will result in a negative number. This is not possible, so the outcome is 0. Multiplying 0 (duty level) with the formula section: "CO_2 credits" will result in: zero costs for the

National CO_2 tax. The effect of this Dutch CO_2 tax for a ceramic company are described in chapter: 5.5.

2.3 The competitive disadvantage for the ceramic industry with a national CO_2 tax system.

A problem that could occur with the Dutch National CO_2 tax is: “carbon leakage” and competitive disadvantage.

The consequence of introducing a parallel National CO_2 tax besides the EU variant can make the final product of Dutch ceramic companies more expensive in comparison with the nearby located competition across national borders in Germany, who do not have a National CO_2 system tax system. This can result in more products being imported from neighbouring countries to the Netherlands due to the price and thus a relocation of de emissions instead of eliminating the CO_2 emissions -> carbon leakage.

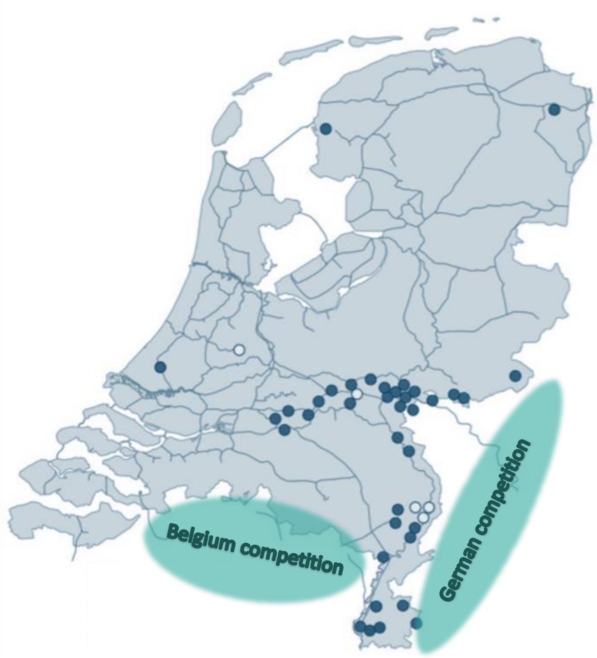


Figure 10 "Location ceramic companies and German competition"

This principle also holds true for the ceramic industry. In interviews with the ceramic industry, it became clear that most of the factories are located at the border with Germany, see Figure 10. The reason for this has to do with subsurface and the amount of clay which is present in that area. For this reason, international competition is in the same region along the German and Belgium border. Introducing a national system has therefore direct impact on the Dutch competitive situation. This will be of no help in reaching our sustainable goals and will result into less jobs in The Netherlands.

3. Hydrogen and the ceramic industry

3.1 A small introduction into the ceramic industry

Within this research the focus is on the ceramic companies which produces bricks. The process of these companies start by searching for the right clay and ends with delivering the products to the customer. For this research the main focus was on the heating process since most of energy is used during this process.

The drying process of the clay starts after the clay is cut in the right dimensions. The clay is dried by re-using the hot air from the kilns. After the drying process the clay is fired in the oven (Figure 11 a). The heat in these kilns comes from burning the natural gas (Figure 11 b). The clay starts at the beginning of a kiln and then moves through the kiln. At the start of the kiln very high temperatures are used and near the end of the kiln the bricks are slowly cooled down by using fresh air. In the kiln the fresh air is flowing towards the end of the kiln and moves through the kiln whereby it is heated by the burning fuel in the middle of the kiln.

Figure 11 a "Kilns in a ceramic company"

b. “Natural Gas Supply via Burner system”

3.2 The ceramic industry needs a sustainable alternative

This paragraph gives insight in the options for a sustainable energy carrier, other than natural gas, for the ceramic industry. Furthermore, the chapter entails information from previous research and the actions which are needed in order to make the industry ready for hydrogen.

3.2.1 Different sustainable energy carriers

As mentioned before, within the sixth cluster electrification could be an option. When taken a closer look at the ceramic industry it seems not possible to use electrification for the entire production process. At this moment it seems that the use of electrical heating elements for firing bricks and ceramic roof tiles will not be sufficient because the heat and/or radiation can’t reach the core of the piled stones (DNVGL, 2018). Sub-processes such as the drying process could be done by electrification, but due to the possible re-use of heating (air) of the firing process this is economically unappealing (DNVGL, 2018).

Using green gas could be an option for the ceramic industry. This option is not further researched within this paper. In terms of reaching a high temperature, green gas is a possible sustainable energy carrier. However, meeting the necessary demand is currently a problem. Current analysis of the industry showed that locally delivering 1/3 – 1/5 of the energy demand can be fulfilled with green gas. So, at this moment in time green gas cannot cover the demand. The industry is now looking into the option of a green gas hub to increase the volumes produced. However, more research is necessary, also to compare this option to hydrogen.

This research focusses mainly on the use of hydrogen as a sustainable energy carrier. Within the ceramic industry there are a number of potential benefits when using hydrogen as an energy carrier (Durusut, et al., 2019):

- Potential retrofit/convert existing equipment instead of full replacement. DNVGL (2018) states the benefit of possible retrofit which makes it economical interesting.
- Reduced impact on the electricity grid and system benefits of hydrogen due to storage facilitation.

Even though hydrogen has a high potential and shows benefits, the change in an energy source also brings challenges. These challenges are not necessarily showstoppers (Durusut, et al., 2019). Currently, DNVGL is working on their largest project in a consortium of 35 parties to develop a burner technology for high-temperature processes (glass, ceramic, steel) to make it suitable for hydrogen. This consortium consists of burner manufacturers, end users, fuel suppliers and transport and distribution companies. The outcome of this project is rather valuable for the ceramic industry and their sustainable future.

3.3 What challenges does hydrogen bring?

3.3.1 What happens to the product?

The temperature, oxygen percentage, CO_2 percentage and the degree of radiation determines among other things, the product properties like color and hardness (DNVGL, Verkenning naar mogelijkheden om aardgas te vervangen in industriele verhittingsprocessen, 2018). So, when using Hydrogen (H2) instead of natural gas (CH4) the chemical reaction when adding surrounding air to the process changes. However, the exact outcome or influence on the end product is unknown. Research and experiments are now taken place to investigate the effect.

3.3.2 NO_x challenges

Natural gas produces NO_x, however when using hydrogen the amount of NO_x could rise. Currently the ceramic industry, focusses on minimizing the NO_x emission. The reduction of NO_x emission when using natural gas has been a process of many years. Finally, it was reduced by choosing another burning process which lead to a lower temperature of the flame. This could also be possible when using hydrogen. However, the type of burners which can be used in the ceramic industry with hydrogen are still researched. Thus, when researching the type of burner, the NO_x emission should also be taken into consideration.

In addition, the government makes policy on the amount of NO_x which is tolerable. However, the government should take into consideration in which industry the most NO_x emission could be reduced in relation to the investment needed. Technically there are some measures that could be taken (Durusut, et al., 2019):

a. Lean combustion; this is a technique where the flue gas is re-used and adds more surround air to the process. This way the NO_x stays in circulations. However, license holders are not excited by this solution. Other options are using pure oxygen or using different burners which have a better cooling system.
b. Dilution; this technique replaces the use of surrounding air by a specific gas of substance
c. Chemkin; this technique focusses on using steam and minimizes the use of flue gas

As mentioned, the type of burner could also be a technical measure. All of these NO_x possibilities (and maybe even more) need to be further researched.

3.3.3 Permits

Without exemption, ceramic companies have permits that limit the emissions of NO_x by applying best available techniques. These limits are usually no problem to reach when using natural gas, but may be too low when using other alternative, like hydrogen as a sustainable energy carrier. The ceramic industry has to be aware they are not trading one problem for another. Because of the strict nitrogen policy in the Netherlands, the location of many companies close to nature areas classified as Natura2000 have lower limits set in the permit and might be facing a problem when transferring to hydrogen whereby this limit is likely to be exceeded.

On the other hand, there seems to be viable ways to reduce the NO_x-production to lawfully acceptable levels. These include recovery and reuse of the exhaust air in the kiln as well as diluting the exhaust air with fresh air. As an end-of-pipe treatment also techniques are available to filter the NO_x-emission from exhaust air, although these are quite expensive.
Something that also still needs to be investigated is a special design of the burner tip that mixes in a right aerodynamical way the hydrogen with the air (or oxygen) that is needed to burn the fuel. A well-designed burner may lead to cooler fire temperatures that lowers the NO_x-content. However, this research is still in progress and will probably be finished at the end of 2021.

In the case that NO_x-levels cannot be reduced below limit values, ceramic companies may have to discuss the phenomenon with the authorities. As it is finally up to the authorities to determine the policies.

3.3.4 Burners

In the tunnel kiln, the fire zone is quite extensive, and a large quantity of small ceramic burners create a kiln atmosphere that allows ceramic products to be produced at stabile temperature levels.

Because of the lower density and different caloric values of the hydrogen as a fuel, the ceramic industry probably cannot use the same burners that are installed right now. Unless of course the introduction of hydrogen is mixed in low quantities in the current natural gas stream. Probably up to a hydrogen volume of 20% can be added to natural gas for current tunnel kilns to be used as they are. It is not known yet, until what percentage the same burners can be used with adding hydrogen. This needs further investigation.

Since there is currently not a single ceramic product produced by using hydrogen, there is still a lot of research, experimentation and burner development needed. Theoretically using hydrogen would be possible, however it has not been proven yet. These experiments are now taking place under laboratory conditions and are foreseen in practice soon after laboratory results are available (probably end of 2021).

Preferably production plants use the same tunnel kiln as is installed now. If not, natural renovation moments in the future need to be used to install a new burner installation and since tunnel kilns are investments for at least 3 decades, depending on when individual companies installed their tunnel kiln, that may take a while. If the current tunnel kiln can be changed in such a way that only the burners would be changed, which seems like the most likely situation, the use of 100% hydrogen could be realized much quicker. As mentioned before, these kinds of burners first have to be designed and produced before they come available for ceramic companies.

3.3.5 Pipeline and fittings

Usually, the ceramic production plants in The Netherlands use natural gas as an energy carrier and piping and fittings are state of the art. The properties of hydrogen makes a screening of the existing distribution network and used materials for transporting hydrogen within the ceramic company necessary. When using a mix of hydrogen and natural gas, another system of pipeline and fittings might be needed. In case the plants do not work with substantially higher pressure compared to the regional network operators, there is a chance that the current materials are suitable. Most of the end-users have the same materials as the regional network operators. If this pressure is comparable, then only a verification check is needed.

Further research needs to be done within the field of the supplying hydrogen. The ceramic industry needs a certain quality and a stable supply.

3.3.6 Quality of hydrogen

The quality of the gas that for the production has to be stable and continuous. Variations in the caloric quality of the gas being injected in the kiln have to be avoided as to better control the process conditions in the kiln. This also guarantees an optimal energy efficiency when firing ceramic products.

Also a mix of natural gas and hydrogen is probably not a problem. However, a producer needs to know the properties of the mixture at all times. Little variations in the quality of hydrogen when only a small amount is added to natural gas will not cause a problem, but when the share of hydrogen (in the future) is larger, this will be more important. When there are more fluctuations in quality there is a need for (extra) peripheral equipment that monitors and/or controls the final quality of the mixture added and/or warns in case of exceeding limit values.

3.3.7 Safety

The use of hydrogen as an energy carrier demands the revision of safety procedures on the ceramic production site. Safety is already an important topic with the use of natural gas. Hydrogen has different properties that may require more or other kinds of: safety precautionary measures, detection systems and installations.

3.3.8 Other costs

Besides the costs of implementing the technical solutions also non-technical costs should be considered. An example is the cost of site downtime due to implementing the technical solutions. Other costs such as the research and experiments, training and implementing safety solutions are of importance.

4. The National hydrogen backbone and infrastructure opportunities for the ceramic industry

4.1 The planning of the hydrogen backbone versus the location of the industries

This paragraph explains the planning of the availability of the parts of hydrogen backbone and the location of the ceramic industry. It shows a deeper analysis on the distance of the industries regarding the backbone by the use of Gasunie's Energy transition App. An important note is that this chapter is based on forecasts.

4.1.1 Planning of the hydrogen backbone

	Hoofdtrajecten backbone	Jaartal beschikbaar voor ombouw	
1	**Rib NO-NL** (Eemshaven-Emmen)	2023-2024	Regionaal
2	**Rib Rotterdam**	n.v.t.	Regionaal
3	**Rib Amsterdam**	2025	Regionaal
4	**Rib Zeeland**	n.v.t.	Regionaal
5	**NO-NL – IJmond**	2024-2025	Nationaal
6	**IJmond – Rijnmond**	2025	Nationaal
7	**Rijnmond – Zeeland**	2026	Nationaal
8	**NO-NL (Elim) – Limburg**	2024-2025	Nationaal
9	**Verbinding Ravenstein – Ossendrecht**	2028-2029	Nationaal
10	**Export DE 1** (via Tjuchem – Oude Statenzijl)	2026	Internationaal
11	**Export DE 2** (via Elim – Vlieghuis)	n.v.t.	Internationaal
12	**Export DE 3** (via Ommen – Winterswijk/ Zevenaar)	2024-2025	Internationaal
13	**Export BE** *(via Beekse Bergen – Hilvarenbeek)*	2029	Internationaal

Figure 12 "Initial planning Gasunie hydrogen backbone"

The decrease of natural gas demand makes it possible for Gasunie to reconstruct the existing transport network so that some pipelines become available for hydrogen. The basic principle here is that the natural gas market must be supplied at all times. According to the current planning, the first parts of the national backbone will be available in 2023-2024 between Eemshaven-Emmen. These parts are in the North of the Netherlands, which in the years after will be followed by a connection in more southern areas. Between 2024-2025 parts of the backbone will be built for multiple regions. The National connection will be made between 2024-2029, parallel to the international connection. Figure 12 shows a more precise planning. This planning is highly dependent on several factors like, the extend of financial contribution of the Dutch government and for example, the contracted capacity by final users. Yet for this research, a boundary condition is that the backbone will be realized.

Three conditions that are leading with regards to the planning are:

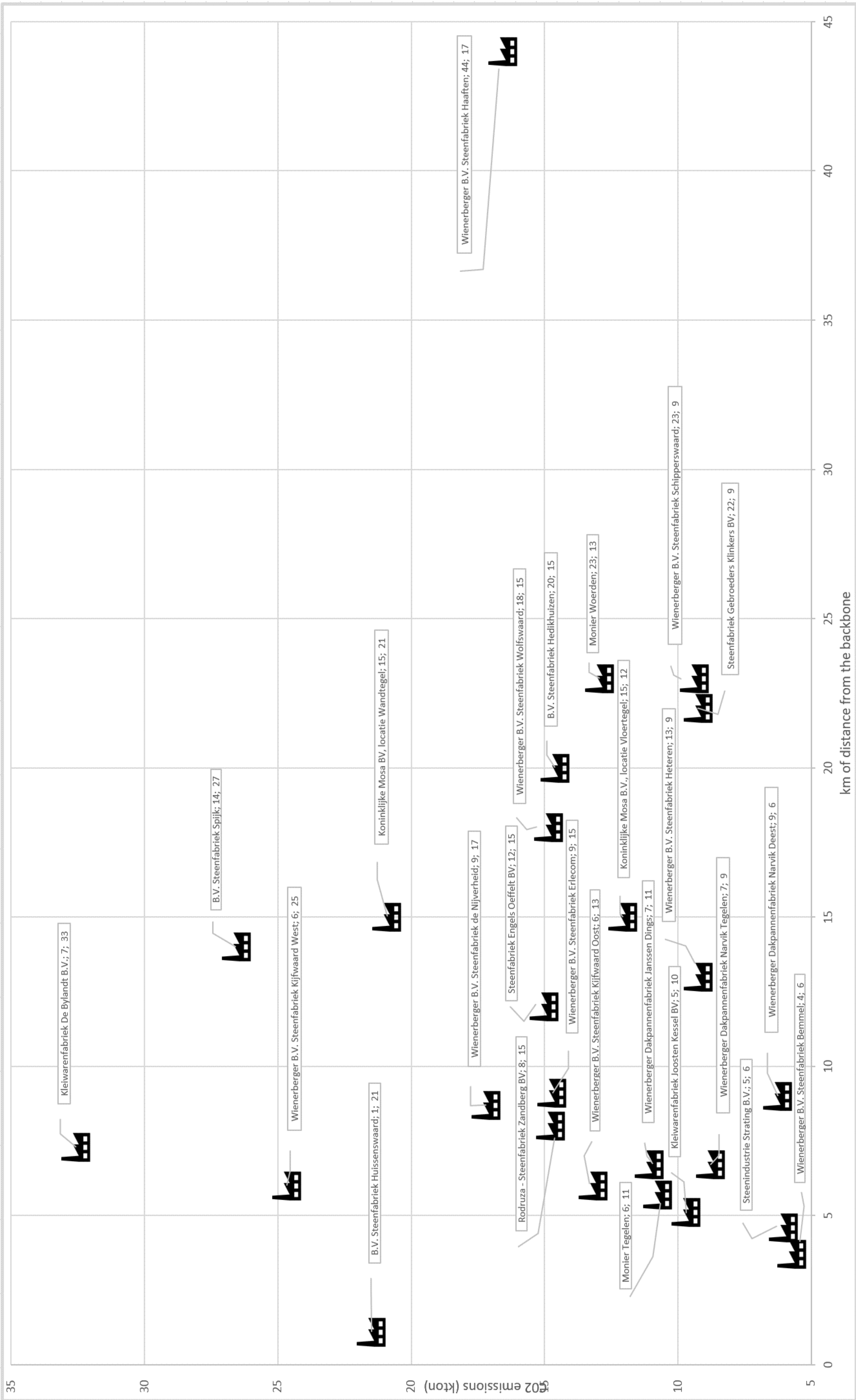
- Not all pipelines that are going to be used for the backbone are available on the short term.
- Furthermore, the time needed for reconstruction per trace is three years from the moment of FID (Final Investment Decision). This timeframe is based on dependency on permits, delivery times of material and the construction itself.
- The third condition is regarding organizational capacity: not all traces can be reconstructed simultaneously, as there needs to be sufficient capacity to supervise these projects

4.1.2. Location of the ceramic industry regarding the hydrogen backbone

The combination of the planned location of the hydrogen backbone versus the location of the ceramic industries results in the figure below. It shows three maps: the first map shows the location of the hydrogen backbone in 2024, consisting of currently existing infrastructure (blue) and new infrastructure that will be constructed (yellow). The second map shows the location of the ceramic industries, and the third map is a combination of both: the location of the ceramic factories with respect to the hydrogen backbone. The third map shows that most of the ceramic factories are located close to the hydrogen backbone.

When taken a closer look on the ceramic industry and the hydrogen backbone, it can be seen that several ceramic industries are located close to the backbone. With the Energy transition App, the locations of the industries can be overseen and potential clusters can be made, which are included in Appendix IV. These clusters consist of the ceramic industries and EU-ETS companies that are in the same area and can benefit from a collaboration to reduce costs.

But before more in depth analysis is shared, Figure 13 on the next page presents the first analysis of the ceramic companies and their vector distance to the planned hydrogen backbone vs. their CO_2 emission rates in kton. In general it can be stated that the closer a company is located to the backbone the bigger the potential is to be connected. But distance does not always hold true. Also the volumes consumed matter and the ability to cluster consumption of hydrogen with companies located nearby. Chapter 4.2 will explain the considerations in more detail for connecting to the hydrogen backbone.


Wienerberger B.V. Steenfabriek Haaften; 44; 17
Wienerberger B.V. Steenfabriek Schipperswaard; 23; 9
Steenfabriek Gebroeders Klinkers BV; 22; 9
Monier Woerden; 23; 13
B.V. Steenfabriek Hedikhuizen; 20; 15
Wienerberger B.V. Steenfabriek Wolfswaard; 18; 15
Koninklijke Mosa BV, locatie Wandtegel; 15; 21
Koninklijke Mosa B.V., locatie Vloertegel; 15; 12
B.V. Steenfabriek Spijk; 14; 27
Wienerberger B.V. Steenfabriek Heteren; 13; 9
Wienerberger Dakpannenfabriek Narvik Deest; 9; 6
Wienerberger B.V. Steenfabriek de Nijverheid; 9; 17
Steenfabriek Engels Oeffelt BV; 12; 15
Wienerberger B.V. Steenfabriek Erlecom; 9; 15
Wienerberger B.V. Steenfabriek Kijfwaard West; 6; 25
Kleiwarenfabriek De Bylandt B.V.; 7; 33
Wienerberger B.V. Steenfabriek Kijfwaard Oost; 6; 13
Wienerberger Dakpannenfabriek Janssen Dings; 7; 11
Wienerberger Dakpannenfabriek Narvik Tegelen; 7; 9
Rodruza - Steenfabriek Zandberg BV; 8; 15
Kleiwarenfabriek Joosten Kessel BV; 5; 10
Steenindustrie Strating B.V.; 5; 6
Wienerberger B.V. Steenfabriek Bemmel; 4; 6
B.V. Steenfabriek Huissenswaard; 1; 21
Monier Tegelen; 6; 11
0
5
10
15
20
25
30
35
40
45
km of distance from the backbone
5
10
15
20
25
30
35
CO2 emissions (kton)

4.2 Analysis of scenario's to connect industrial clusters to the hydrogen backbone by 2030

By starting the analysis on the possibilitiy of the connection to the hydrogen backbone with Gasunie's existing infrastructure, there are multiple policy-related uncertainties that Gasunie is facing. These uncertainties are seen as opportunities that require decision-making outside of our regular day-to-day procedures and therefore need more research and collaboration with multiple parties. These opportunities provide information about the developments that still need to be taken in order to facilitate the connection to the hydrogen backbone. Having quite some opportunities for future research complicates the precision of measuring the distance from the backbone to the clusters and the corresponding costs and benefits from the infrastructure. The opportunities are elaborated below. Despite these, this chapter includes the three possible infrastructure scenario's, a first insight in the corresponding costs and boundary conditions.

4.2.1 Opportunities to handle

Opportunity 1) Tie-ins to the backbone - Connecting the clusters to the backbone require tie-in points. Tie-ins are parts of the backbone where the pipelines gather. The locations of these tie-ins are not decided yet, which means that a cluster that is located close to the backbone can still require a significant number of kilometers to get connected.

Opportunity 2) The division of roles between the regional network operators and Gasunie - The role of each party is not set in stone. Currently the roles of the regional network operators are that they oversee the regional pipelines (20 mbar-8 bar) that are connected to the national pipelines from Gasunie (RTL = 40 bar, HTL = 60 bar). To connect the industries to the backbone, the amount of bar needs to be lowered to make the energy suitable for usage. It is not decided yet how Gasunie and the regional network operators are dividing the responsibilities regarding hydrogen transportation.

The national sector organization of the network operators, Netbeheer Nederland, visualized two scenarios in Figure 14 "Connecting to the backbone - regional network operators". On the left the current situation can be seen: the customer (the orange icon) is connected to the network of the regional network operators, and this network is connected to the national gas transport network. The connection to the hydrogen backbone is visualized in scenario A (green) and B (orange). In scenario A: the customer is connected to the regional network, and via the regional network the customer is connected to the hydrogen backbone. In scenario B: the customer is directly connected to the hydrogen backbone. These two scenarios have large implications, as with scenario A the customer will be connected to closely located regional pipelines, and with scenario B Gasunie must expand current infrastructure to connect its customers to the hydrogen backbone. The amount of newly build pipelines has large implications for the costs that are related to these developments.

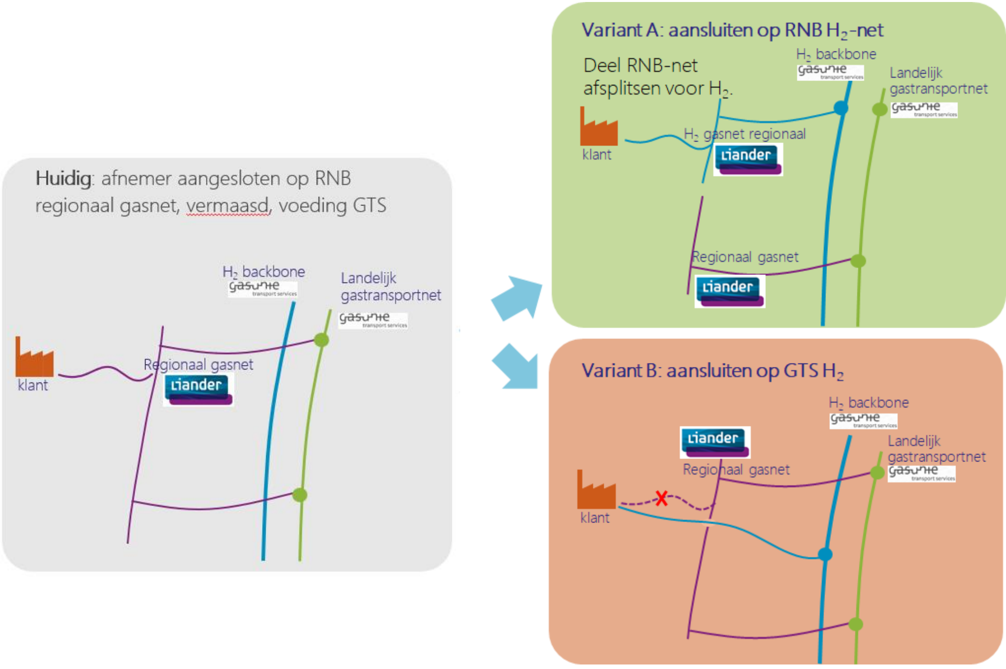


Figure 14 "Connecting to the backbone - regional network operators"

Opportunity 3) In addition to the second opportunity: The costs that accompany the development of the infrastructure for the H2 regional network are not defined yet. Depending on the definition of the roles mentioned in the second opportunity, the responsibility of building the pipelines to expand the network will be at Gasunie or the regional network operators. Normally when Gasunie builds pipelines (HTL & RTL), a higher price per kilometer is calculated compared to the regional network operators. Building pipelines by the regional network operators is a factor of 2-4 cheaper per meter compared to pipelines from Gasunie. Also, the distance is in most cases shorter when the regional network operator builds, because part of the existing network can be used. If Gasunie gets the responsibility to build the pipelines that connect the industries to the backbone, Gasunie should build pipelines that are comparable to pipelines from the regional network operators, as end-users cannot be connected to HTL pipelines due to the corresponding larger volume size of fuel. Or, when regional network operators are in charge of this process, they might need to build H2 pipelines parallel to the regional gas network.

Overall, the price of the pipelines are dependent on the party that builds them, and to what extend the two parties collaborate on this matter. The search for geographical opportunities should be done by comparing the two networks and combine each other's strengths. This can lead to more impactful results than when the two parties operate separated from each other, as it has positive influence on the financial consequences. This required collaboration is studied upon by Netbeheer Nederland and Liander, by examining a case (named Opheusen & Heteren) where the network of GTS and Liander are combined to connect three ceramic industry plants to the hydrogen backbone. This study indicates that collaboration between Liander and GTS makes it possible to lower the costs for all, in comparison to executing in isolation by GTS and Liander. This case also makes clear that the conversion depends on the geography of the existing networks and customers. Appendix III shows the study in 6 visualisations, received by Liander.

Opportunity 4) The availability of other pipelines - In the area of our industrial clusters are other pipelines which are not included in this analysis. The availability of these pipelines can have implications on this analysis as it might provide new possibilities to connect clusters with an existing network of pipelines.

There are three possible scenario's on how to connect industries to the backbone, depending on the existing infrastructure in the area of the clusters. The three scenarios are visualized in Figure 16.

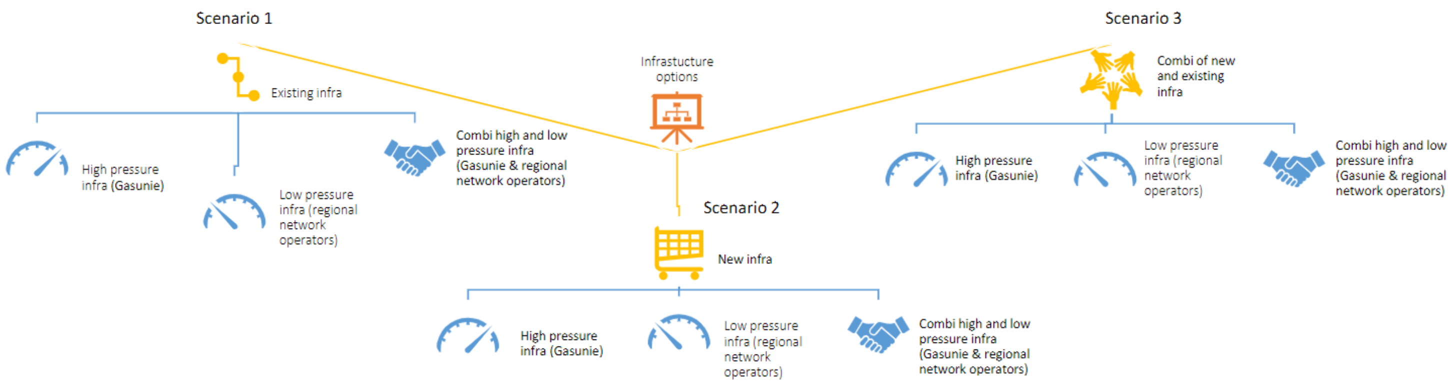


Figure 16 "Scenario's for connecting industries"

The graphic explains that it might be possible to connect the industries to the backbone via existing infra (1), based on new infra (2) and a combination of new and existing infra (3). All scenario's require strong collaboration with the regional network operators.

4.2.2 An example cluster (Brick Valley)

Despite the opportunities to handle, in this report the focus is on one cluster as an example case and briefly go through the different possibilities. This brings insight in which scenario's might be interesting for this cluster, and helps to choose the suitable scenarios for the other clusters in the future (see the clusters in Appendix IV).

The cluster that is used as the example case is called the *Brick Valley.* This is a cluster nearby Arnhem and Nijmegen, which is known as an innovative cluster that sets the example for the other clusters. In Figure 17 the location of this cluster can be seen and the distance to the expected hydrogen backbone (blue line).

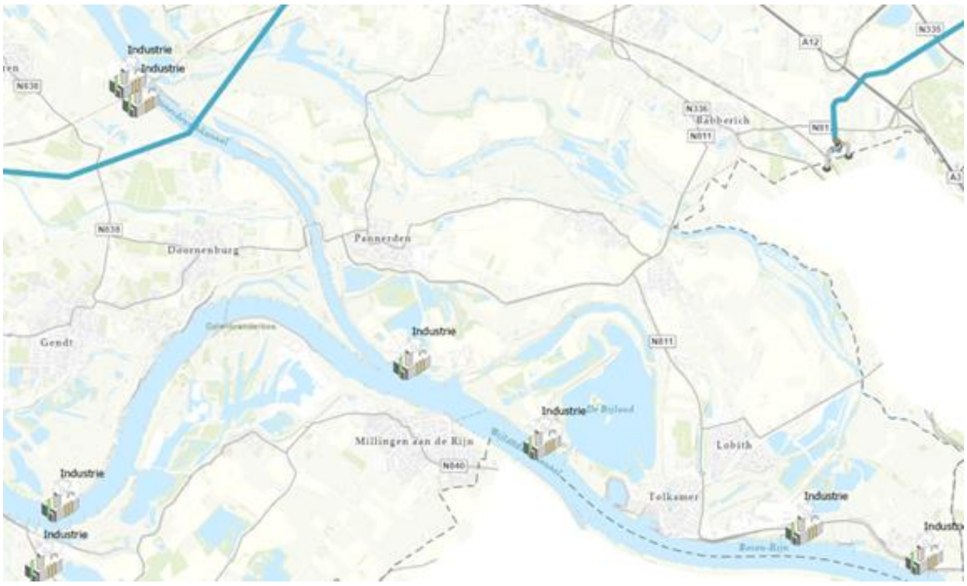


Figure 17 "The Brick Valley location and the expected hydrogen backbone"

<u>First possible scenario Brick Valley – 3) Combination of new and existing infra</u>

In the image below it can be seen that in this area, there are no pipelines from the regional network operators (Figure 18). When using existing infra, it might be possible to use the RTL pipelines to connect the Brick Valley to the hydrogen backbone. If the RTL pipelines are suitable for hydrogen (no other end users than just the industries), the outcome might look like Figure 19. The currently existing regional Gasunie network (red lines) can be seen, and the distance from this network to the hydrogen backbone. In this example case, this connection requires new pipelines of 2,17 and 3,8 kilometers.

Figure 18 "The regional operators network (blue lines) in the area of the Brick Valley - Source: Liander"

Figure 19 "The connection between a new HTL pipeline (purple lines) from the H2 Backbone to the RTL-network (red lines)"

Second possible scenario Brick Valley – 2) New infra

If it is not possible to use the RTL-pipelines for hydrogen, a completely new infrastructure needs to be build. Chances are likely that this will look like Figure 20. This scenario consists of a shared pipeline that divides itself into separate individual pipelines to the industries (from HTL to RTL). Having a shared pipeline provides the opportunity to share the costs. In this example the shared pipeline will be 8,7 kilometers, and the different individual pipelines between the 3-5 kilometers. The corresponding boundary conditions to these measures are explained below.

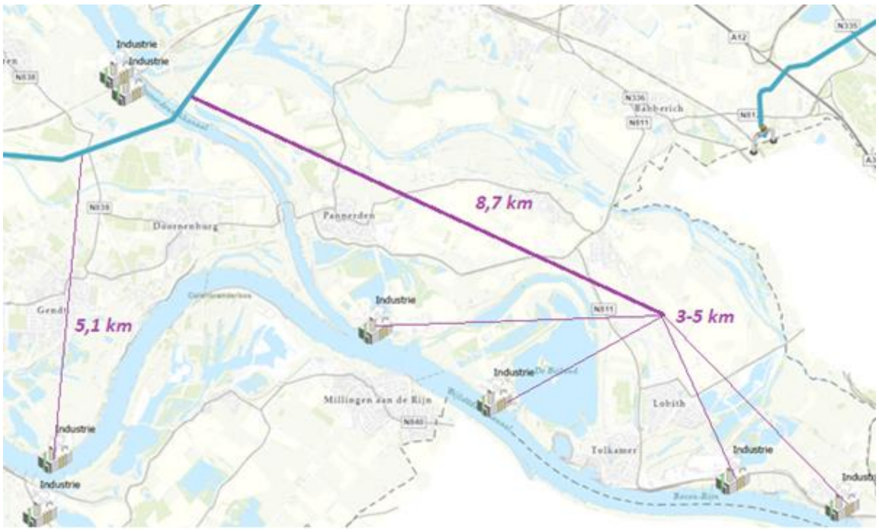


Figure 20 "The new infrastructure to connect the Brick Valley to the hydrogen backbone"

Costs

A large disadvantage of using new infra are the financial consequences: using new infrastructure is approximately four times more expensive than using existing infrastructure for hydrogen, according to the report Hyway27 (2021). This report does not contain the exact prices per kilometer of traces, as this information (investment costs and maintenance costs) can be considered as commercially sensitive outside Gasunie. Some factors that increase costs significantly are routes that cross water (rivers, lakes, etc.), roads, train tracks and tunnels.

Boundary conditions

These scenarios have several boundary conditions: the connection point to the hydrogen backbone is at the nearest location of the backbone and the distance is measured in a direct line (‘as the crow flies' -measurement). There may be obstructions below and above the ground that do not allow a completely straight-line pipeline route in practice. It is common to use a factor of 1,3 – 1,6 to roughly translate the straight-line route to the actual route.

The choice in scenario's and the policy decisions that answer the mentioned opportunities together have a large impact on the measurements and pipelines needed to facilitate the right infrastructure for H2. There needs to be strategic decision making between Gasunie, the Ministry and the regional network operators on the division of roles and responsibilities, the corresponding costs of this decision, and the method of tie-ins to connect the industries to the backbone. On the positive note, it is known that building new infrastructure is rather expensive, yet therefore there is an GOS (gas receive station) at every large city and area to achieve economic optimisation. These stations can regulate the in- and outflow of energy carriers, and therefore we do not start from scratch with the building processes

5. A cost perspective on natural gas for the ceramic industry

This chapter gives insight in the historical, current and future natural gas price for the ceramic industry. First the spread in natural gas costs per year per factory will be explained. A small insight in the historical development of the natural gas price will be presented. Followed by an analyses of the current gas price; effects of the EU-ETS policy; effects of the National CO_2 policy and their outcome on the final product price.

The ceramic industry is a sector that relies mostly on natural gas for their energy. With a total of 40 factories that use about 200 million cubic meters of natural gas. The emissions for the 36 EU-ETS factories in the Netherlands resulted in 517.000 ton CO_2 in 2019 of which around 80% is fuel emission and 20% is process emission. (Cluster-6, 2020).

5.1 There is a large variation in the yearly natural gas costs for a ceramic company.

Analysis of the emission figures published by the Dutch emission authority (NEA, 2020) gave insight in the volumes of natural gas that the EU-ETS ceramic factories consume. It can be stated that a ceramic factory on average consumes 7.000.000 m^3 of natural gas a year (for the methodology to derive the natural gas consumptions from the emission figures see: appendix V). The large-scale ceramic factories in the Netherlands consume about 15.000.000 m^3 natural gas a year, while the smallest in scale consume around 2.000.000 m^3 natural gas a year. So, there is a large variation. The proceeding financial analysis in this chapter will be based on an average ceramic factory that consumes 7.000.000 m^3 of natural gas a year. With the current market price for natural gas: €0,23 (CBS, 2021), the costs for using natural gas by a factory are presented in Figure 21.

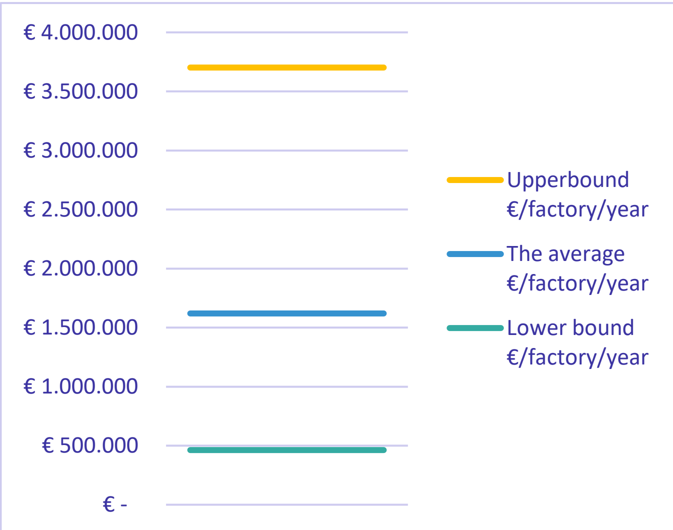


Figure 21 "Spread of natural gas costs – factory/year"

5.2 From a historical perspective, it is clear that the industry prices for natural gas have risen significantly.

The natural gas price has remained relatively stable till 1999. From 2000 the natural gas price went up, this is mainly due to a significant increase of VAT and other duties, see Figure 22 (Energiesite, 2021).

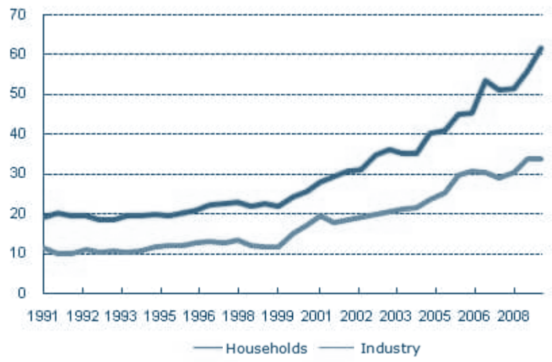


Figure 22 "Historical development of the natural gas price"

5.3 Duties & tax predominate in setting the end-user price for natural gas.

Looking in closer detail to the gas price, it could be stated that the price is a sum of the 3 listed elements below. The price structure of these three elements is pictured in Figure 23. (Essent, 2021).

1. Transmission system costs
   a. The costs for operating and maintaining necessary infrastructure.
2. Delivery tariff
   a. Fixed delivery costs (standing charge)
   b. Variable delivery costs: natural gas price per cubic meter (user costs)
3. Duties & tax
   a. VAT
   b. Energy tax
   c. ODE (a duty that was introduced in 2013 to create funding to produce sustainable energy and to make sure that the use of fossil fuels is mitigated).

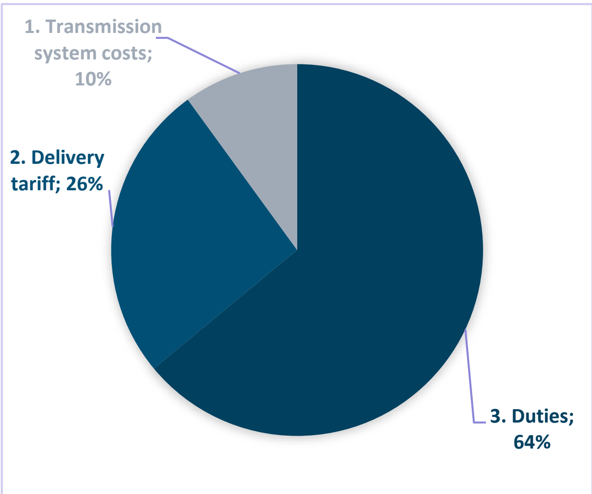


Figure 23"The price structure of natural gas for business tariffs"

Figure 24 shows the cost structure for an average ceramic company (7 mln m^3 natural gas a year). So of the €1.5 mln of costs induced for natural gas around €1 mln is paid for duties; €400 thousand is paid for the delivery costs and approximately €150 thousand for transmission costs. The percentage of duties will rise in the coming years, with the introduction of the EU and Dutch legislation on CO_2.

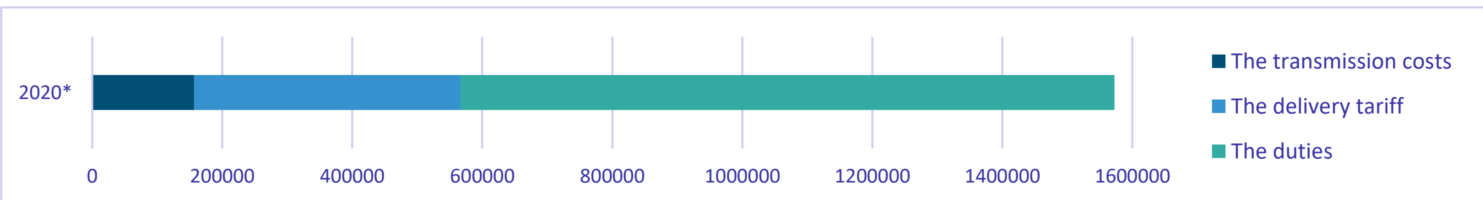


Figure 24 "Cost structure natural gas for an average ceramic company"

5.4 What the EU-ETS CO_2 tax means for a ceramic company in the coming years?

Besides the base cost construction of natural gas, described in the previous paragraph. The ceramic industry is assigned as an EU-ETS industry. This entails that ceramic factories are obliged to pay a CO_2 tax. Actually, this tax is a: "cap-and-trade system". More about this policy is described in chapter 2.2: "The effect of National & EU climate agreement instruments for the ceramic industry".

Shell analysed the impact of this tax in general and stated that if a climate neutral status should be reached in 2050, the EU tax should be at al level of above the 200 euro per ton CO_2 by 2030 (Hatherick, 2020). The todays spot price of one ton of CO_2 is set at: €50,- (EEX, 2021). In order to forecast the EU-ETS costs till 2030 a linear approach is applied (€50 in 2020 -> €200 in 2030). Furthermore, information regarding the dispensation credits for this industry per year is necessary. The ceramic sector association provided us with that information, which is pictured in Figure 25 together with other applied parameters.

Year	Ceramic emissions (ton/year)	Part heating	part process (feedstock)	The assigned ETS (ton credits)	Shortage ETS (# to buy - ton credits)	percentage ETS shortage (%)	CO_2-price per ton	ETS Costs (€)
	Start 15.000; increased linear with 2% per year	*Ceramic emissions*0,8*	*emissions*0,2*	*[part natural gas*0,76]+[part process*0,97]*	*Ceramic emissions - The assigned ETS*	*Shortage ETS/Ceramic emissions*	*linear ascending from €50 to €200*	*Shortage ETS * CO_2-price per ton*
2021	15.000	€ 227.077	3.000	12.030	3.493	23%	€ 65,00	€ 193.050
2022	15.300	€ 303.480	3.060	11.765	3.793	25%	€ 80,00	€ 282.773
2023	15.606	€ 389.452	3.121	11.507	4.099	26%	€ 95,00	€ 389.452
2024	15.918	€ 485.278	3.184	11.253	4.412	28%	€ 110,00	€ 513.124
2025	16.236	€ 591.247	3.247	11.006	4.730	29%	€ 125,00	€ 653.837
2026	16.561	€ 1.028.952	3.312	9.631	7.350	44%	€ 140,00	€ 970.280
2027	16.892	€ 1.190.537	3.378	9.419	7.681	45%	€ 155,00	€ 1.158.419
2028	17.230	€ 1.363.184	3.446	9.212	8.019	47%	€ 170,00	€ 1.363.184
2029	17.575	€ 1.547.217	3.515	9.009	8.363	48%	€ 185,00	€ 1.584.708
2030	17.926	€ 1.742.967	3.585	8.811	8.715	49%	€ 200,00	€ 1.823.137
Total								**€ 8.869.392**

Figure 25 ""Cost calculation EU-ETS costs for a ceramic company a year"

It has been assumed that the yearly CO_2 emissions will rise with 2% a year, this to account for trends like the house shortage in the built environment which leads to higher demand in the ceramic industry (Wennekes, 2021). Finally, we account that 80% of the emissions are heat-related emissions and 20% are process emissions (Cluster-6, 2020).

To determine the yearly consumption costs for natural gas (m^3), a yearly increase of 2% has been assumed, corresponding with the increase of emissions per year. Based on the (EEX, 2021) historical transaction costs for natural gas (2009-2020) a timesieries has been created in order to make a forcasting model to determine the yearly natural gas transaction prices from 2021-2030 (see for more information about the methodology and forcasted values appendix VI). The forcastingmodel is based on a 95% confidence interval, where the upperlimit is applied to account for a correct of external influences like closure of the Dutch gasfields (Groningen) which could create higher transactions costs for gas in the coming years. See Figure 26, for the historical and forecasted transaction price of natural gas.

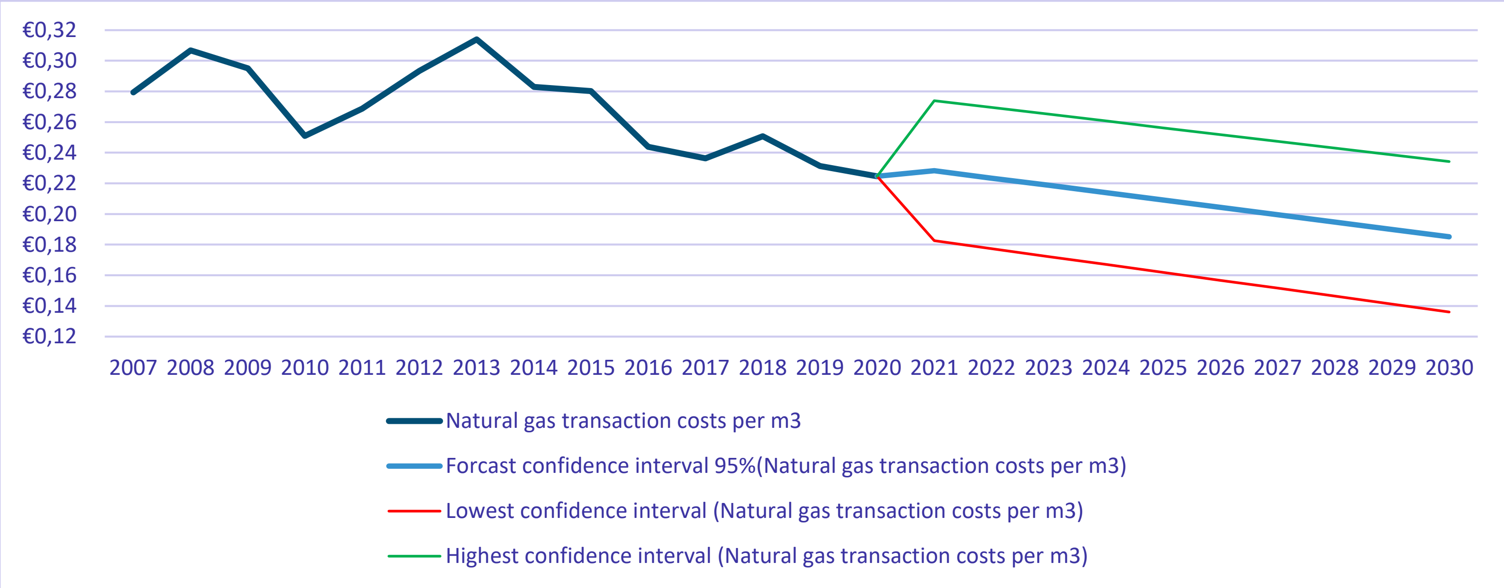


Figure 26 "Time series forecast model natural gas transaction prices 2021-2030"

With the forecasted transactions price of natural gas and forecasted consumption (considering the 2% annual increase), Figure 27, outlines the yearly costs for the consumption of natural gas that a ceramic company will have from 2021-2030.

The information of Figure 25 & Figure 27 combined gives insight in the effects of the natural gas consumption costs and the EU-ETS costs of a ceramic factory from 2021-2030. More information about the transaction costs is presented in chapter 5: "Duties & tax predominate

Year	Forecast natural gas consumption	Forecast transaction price natural gas	Standard natural gas costs
	2% annual increase	*95% confidence interval (timeserie 2007-2019)- upper limit applied*	*average natural gas consumption * yearly increase of consumption: 2% * natural gas market price*
2021	7.000.000	€0,27	€ 1.572.353
2022	7.140.000	€0,27	€ 1.956.063
2023	7.282.800	€0,27	€ 1.962.977
2024	7.428.456	€0,26	€ 1.969.407
2025	7.577.025	€0,26	€ 1.975.330
2026	7.728.566	€0,25	€ 1.980.723
2027	7.883.137	€0,25	€ 1.985.564
2028	8.040.800	€0,24	€ 1.989.829
2029	8.201.616	€0,24	€ 1.993.492
2030	8.365.648	€0,23	€ 1.996.528

Figure 27 "forecasted natural gas consumption and transaction prices 2021-2030" in setting the end-user price for natural gas." The effect of these forecasted costs are presented in Figure 28 in two different views. On the left side, costs are presented in separate bars and on the right side cumulative.

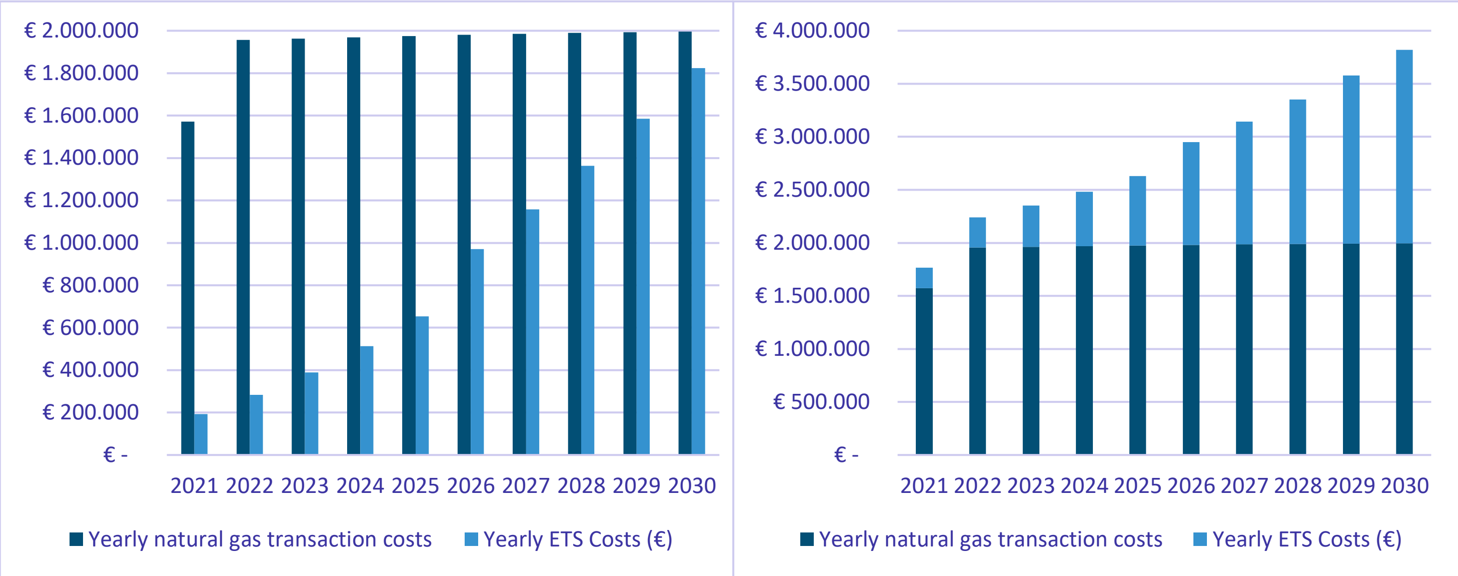


Figure 28 "Cost-projection yearly natural gas & EU-ETS costs till 2030 for an average ceramic factory"

It can be concluded that the EU-ETS tax will have a large impact on the ceramic industry. By 2030 the costs will have almost doubled due to the EU-ETS tax. This is a major amount and does not include the new introduced National tax yet.

The rise in costs for the EU-ETS tax is explained by the combination of shortage in dispensation credits and growing expense per ton CO_2. See for more details Figure 25 ("Shortage ETS - # to buy- ton credits" & "CO_2-price per ton")

5.5 What the Dutch CO_2 tax means for the energy costs of a ceramic factory in the coming years.

This effect is shown in the Figure 29 and based on the methodology described in chapter 2.2.2.

Year	Ceramic emissions (ton/year) Start 15.000; increased with 2% per year	Dispensation credits (ton credits) Ceramic emissions* reduction factor linear*benchmark reduction factor	CO_2-tax Policy is start €30 linear ascending with €10,56 a year	EU-ETS CO_2-price per ton Linear ascending from €50 to €200
2021	15.000	12.030	€ 30,00	€ 65,00
2022	15.300	11.765	€ 40,56	€ 80,00
2023	15.606	11.507	€ 51,12	€ 95,00
2024	15.918	11.253	€ 61,68	€ 110,00
2025	16.236	11.006	€ 72,24	€ 125,00
2026	16.561	9.631	€ 82,80	€ 140,00
2027	16.892	9.419	€ 93,36	€ 155,00
2028	17.230	9.212	€ 103,92	€ 170,00
2029	17.575	9.009	€ 114,48	€ 185,00
2030	17.926	8.811	€ 125,04	€ 200,00

Costs National CO2 tax

Figure 29 "cost calculation National CO_2 policy"

Figure 29, implies for a ceramic company that no extra costs will incur due to the Dutch CO2 policy till 2030. This is based on the assumptions mentioned in paragraph 5.4, where the future EU-ETS CO_2 price per year is determined.

The second part of the equation defines that no extra costs occur because the EU CO_2 price per ton is higher than the Dutch CO_2 price in every year. That part of the equation will therefore result in 0 (or a negative number, but this is not possible, so 0 should be applied). So, the whole calculation will also result into zero, and therefore results in no costs for the National CO_2 tax.

5.6 What the extra duties will do with the final product price in the ceramic industry.

Expert judgement within the ceramic industry indicated that on average 30% of the final product price consists of energy costs. An average unit product price in the ceramic industry is around €0,25. So that means €7,5 cent (30%) is for energy and 18 cent (70%) for the other costs/the profit margin. By 2030 these energy costs will almost double because of the EU-ETS costs (see Figure 31). To simplify this means 15 cent (46%) for energy and 18 cent (54%) for other costs/profit margin. Final products will therefore cost around €0,33, this means a 32% raise of the final product price. See Figure 30 for the percentages.

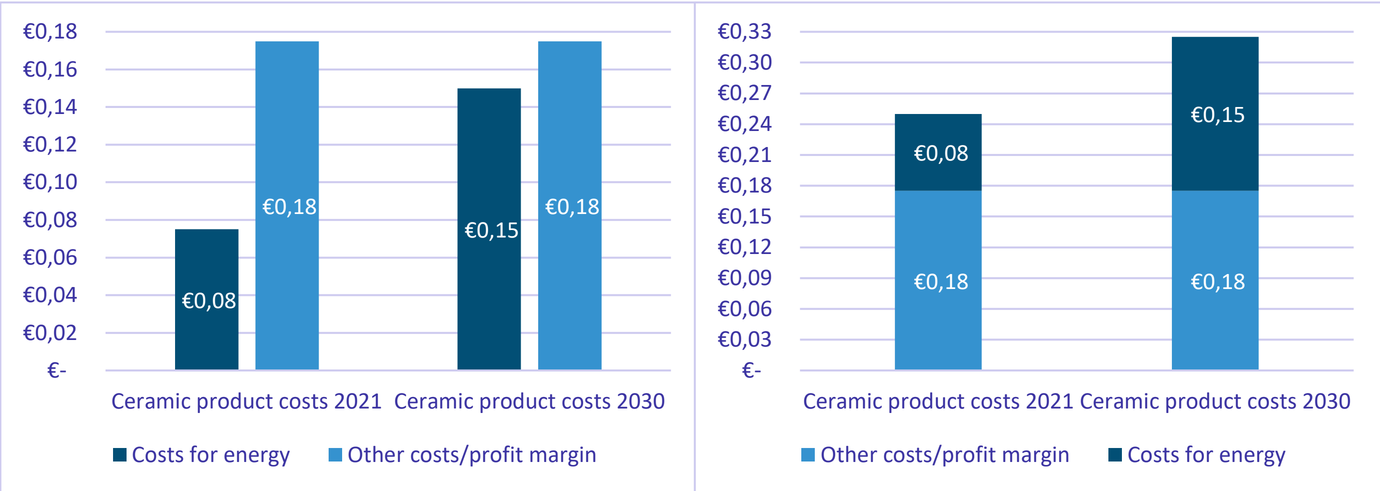


Figure 31 "Absolute cost construction ceramic products 2021 and 2030"

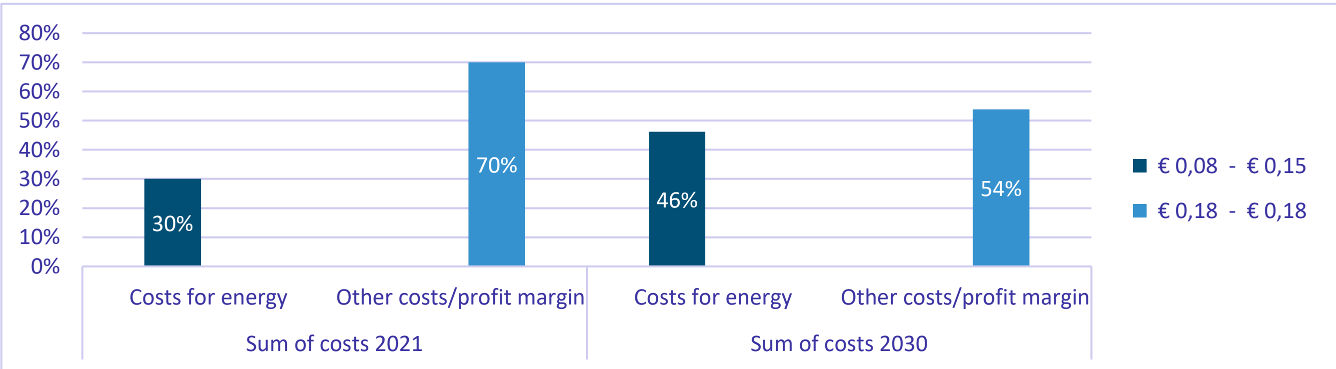


Figure 30 "shift in percentage of the final product price due to the EU-ETS tax"

The question will be what happens with competition like the wood industry for construction of buildings or a sector like: concrete, who are not part of the EU-ETS system and do not have these extra costs. This could have a negative effect on the ceramic industry. The next ten years at least 1 million new houses will be built and 230.000 renovations are expected (KNB, 2020), but bigger shares for these projects could go to sectors that offer different materials and which are not charged with the EU-ETS scheme. This is also dependant om the policy pathway of our new government as explained in chapter 2.2.

6. A cost perspective on hydrogen for the ceramic industry

As can be seen in the previous chapter, the costs for natural gas will greatly increase for ceramic companies due to the EU-ETS system in the coming 10 years. It is therefore important for the ceramic industry to find a sustainable alternative for natural gas. As described in the first chapters, hydrogen is a promising alternative. This chapter describes what the options are for hydrogen and which costs should be considered.

6.1 Transport medium according to distance and volume

Chapter 4 gives insight in the location of the hydrogen backbone vs the location of the ceramic industry. This chapter concluded that in some cases existing infrastructure can be used and in some cases new infrastructure has to be built in order to transport hydrogen. What has not been covered so far, is the way that hydrogen can be transported efficiently based on volumes and kilometers to cover with transport.

(Bloomberg, 2020), researched different transportation mediums according to volume and distance. And the HyWay27 research (HyWay27, 2021) defined the transport volumes in PJ/year. The outcome of this research is presented in Figure 32.

A ceramic company that uses 7 million m^3 natural gas a year is equal to a use of around 0,25PJ a year. This implies that transport by means of compression could be an option when it only concerns one company that will use hydrogen and clustering is not possible. But we have also seen that transport with the use of existing infrastructure (natural gas) is four times cheaper than building new infrastructure, this could outset transport by means of trucks. Because transporting 0,25 PJ per year is similar to having 25 truck runs a day to meet the necessary demand.

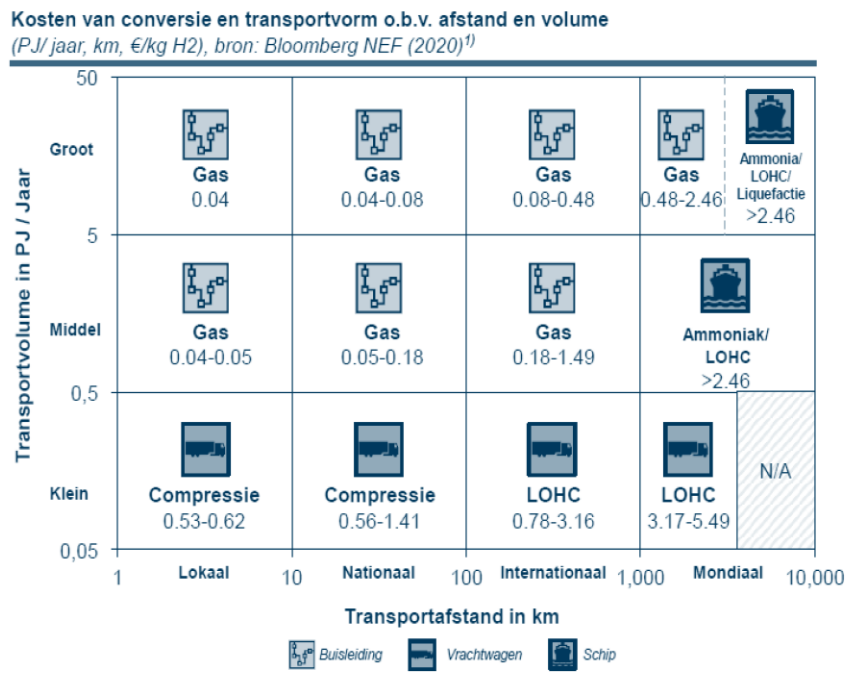


Figure 32 "hydrogen transport costs based on distance and volume $/kg H2" (2019)

Our advice would be to further investigate the following pathways:

Frist pathway: blending a % of hydrogen with natural gas

- It could be interesting to investigate whether trucks are a suitable pathway
- It could also be interesting to investigate whether hydrogen can be added in the main gas connection
  - However, this is dependant on the different end-users and their requirements for e.g. the hydrogen quality

Second pathway: 100% hydrogen

- We advice to use existing infrastructure when possible
- Also try to cluster demand with other factories nearby (not necessarely of the same sector)
- When existing infrastructure is not available, we advise that the specific case should be analysed by Gasunie in cooperation with the regional distribution operators.

Thrid pathway: virtual pathway to make the cerarmic industry sustainable

- Virtual guarantees of origin could be a solution for factories which are located far from existing infastructure and have high demands for hydrogen, we advise that this pathway is included in the EU ETS system
- Currently, the virtual guarantees of origin are not (yet) approved as an instrument within the EU ETS system

Figure 33 "Pathways from a cost perspective"

6.2 The commodity price of hydrogen

A lot of analysis has been conducted to determine the end user price of hydrogen per kilogram. PBL analyzed various existing research about the production costs of green hydrogen by 2030 (Hoogervorst, 2020). The production costs can range between €1,27 and 4,75 per kg of hydrogen in 2030. The difference has to do with the assumptions they made, like: investment costs, electrolysers, running hours etc. PBL indicates that costs do not reflect our national costs because for example forecasted wholesale prices are used. These wholesale prices are only part of the production costs of electricity from sun/wind.

	2030			2050			Beschrijving
Bron	Min.	Gem.	Max.	Min.	Gem.	Max.	
CE Delft (2018)	2,28	2,92	3,75	-		-	NL. Wind.
CE Delft (2018)	1,82	2,24	2,66	-		-	Marokko. Zon.
CE Delft (2018) & *bewerking*	2,84	3,75	4,75				NL. E-prijzen uit KEV.
DNV GL (2019b)	-		-	1,05		1,35	EU. E-prijs van 0 €/MWh en 3.000 uren
DNV GL (2019b)					1,80		EU. E-prijs van 29 €/MWh en 8.000 uren
TNO en DNV GL (2018)		2,94		-		-	NL. 2025 waarden; elek. prijs (niet alleen groen)
BloombergNEF (2019)	1,27		2,64	0,73		0,91	Wereld
TKI Nieuw Gas (2018)	3,00		3,50	-		-	NL. MW-schaal
TKI Nieuw Gas (2018)	2,00		3,00				NL. Schaal 10-100 MW
IEA (2019)	1,73		3,64	1,45		2,55	Europa
METI Japan (2017)		2,82			1,91		Japan
Glenk & Reichelstein (2019)	2,00		2,50	-		-	Duitsland
IRENA (2019)		1,73		0,86		1,13	Wereld. Wind.
IRENA (2019)		1,45		1,08		2,36	Wereld. Zon.
Weeda (2019)	2,60		4,20	-			NL. Aardgasprijs uit KEV
Min/Max	1,27		4,75	0,73		2,55	
Gemiddelde		2,72			1,43		
Gemiddelde min/max	2,17		3,40	1,04		1,66	

Figure 34 "Cost price of hydrogen in €"

6.3 The colour of hydrogen and related prices (2025-2050).

The big question of course is what hydrogen prices will do for the ceramic industry in the coming years. This is not easily answered because different types of hydrogen exist and often each variant is labeled with a certain color, see for more information Figure 35.

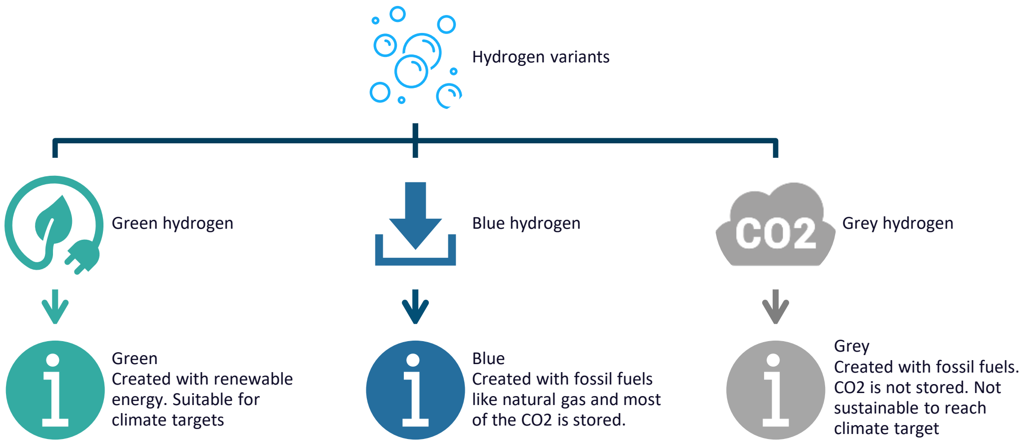


Figure 35 "Types of hydrogen"

As Figure 35 explains, the colour of hydrogen is determined by the sources of energy and the production pathways which are used to create hydrogen.

Figure 36, presents 12 different hydrogen chains that are modelled with a simulation tool developed by Gasunie. The chain costs represent the commodity costs for 1 kg of hydrogen up and including the costs of the National transport grid. Detailed information about the chain analysis, input parameters and sources are presented in: appendix VII.

It is important to mention, that one chain is not a hydrogen chain: chain 30. This is the hydrogen equivalent for natural gas to offer a perspective in the hydrogen chain prices related to a gas-based fossil alternative.

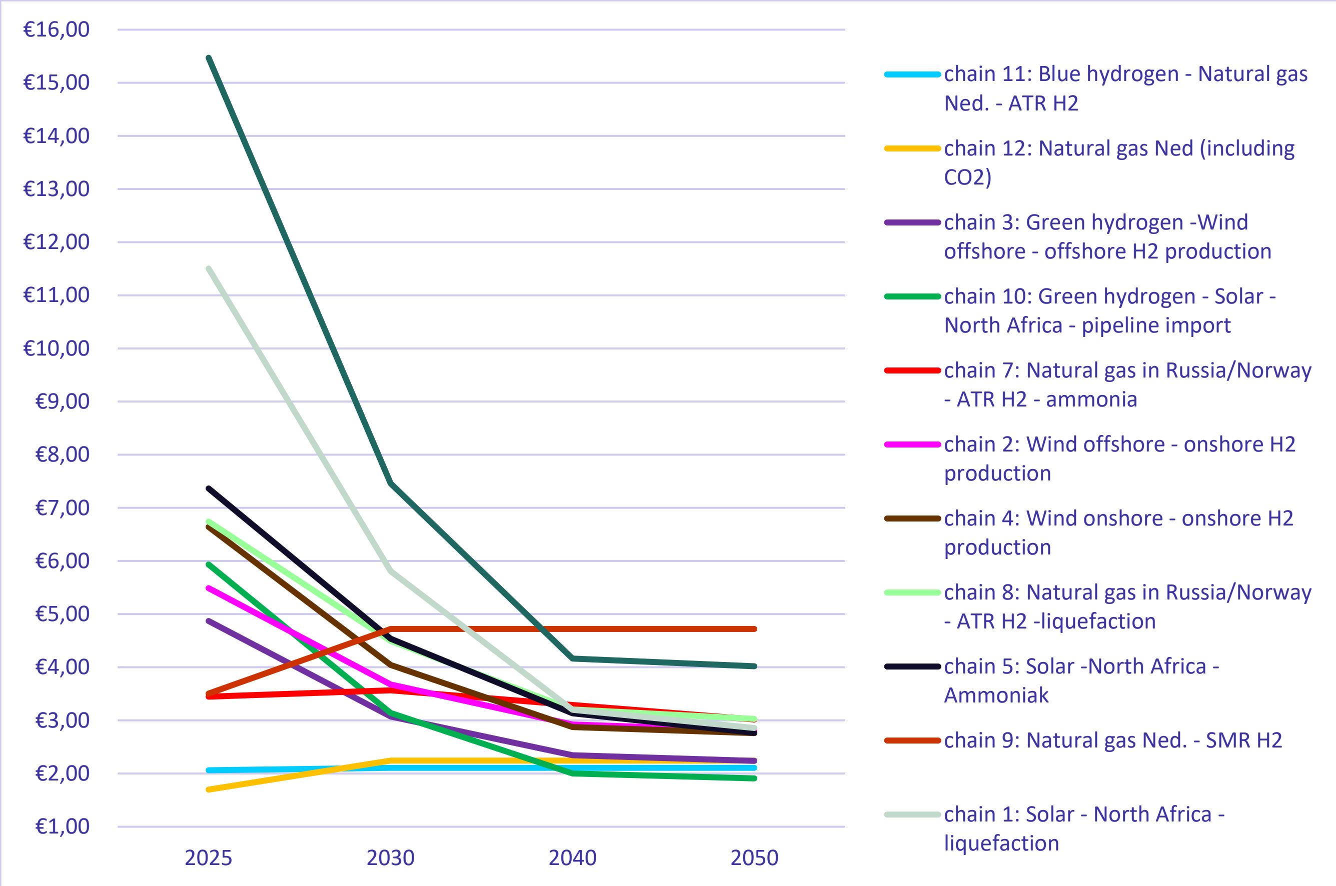


Figure 36 "Hydrogen chain prices"

When considering longterm prices (2050), analysis shows that green hydrogen will be the cheapest option. Especially green hydrogen produced by sun in Marrocco and transported per pipeline to the Netherlands, this will cost €1,91. The next runner up for green hydrogen is hydrogen produced in the Netherlands with offshore wind and converted offshore with a price of: €2,24 in 2050.

The first point in time where hydrogen is cheaper than natural gas is 2030. Blue hydrogen will be 14 cent cheaper. By 2040 green hydrogen will also be 25 cent cheaper than natural gas.

When focusing on short term price developments of hydrogen: 2025-2030. Figure 37 presents the most promising hydrogen chains (blue & green).

What could be concluded is that in the nearby future (2025), blue hydrogen (chain 11) produced with an ATR technique is the cheapest option: €2,06. This is also the case in 2030 with €2,11. The rise in costs is explained by the costs induced due to rising CO_2 prices modeled in the simulation tool (Hatherick, 2020).

The cheapest green chain in 2025 is chain 3 (€4,87): electricity made from wind offshore and processed offshore by an electrolyser. The costs of chain 3 (wind) will lower to: €3,08 by 2030. When considering sun, the cheapest option in 2025 is chain 10 (€5,95): sun produced in Morocco converted to hydrogen and transported by pipeline to the Netherlands. The costs of chain 10 (sun) will lower to: €3,14 by 2030. These 3 blue and green chains are pictured separately in Figure 37, with a price development till 2050. These 3 chains will also be used further chapter analysis.

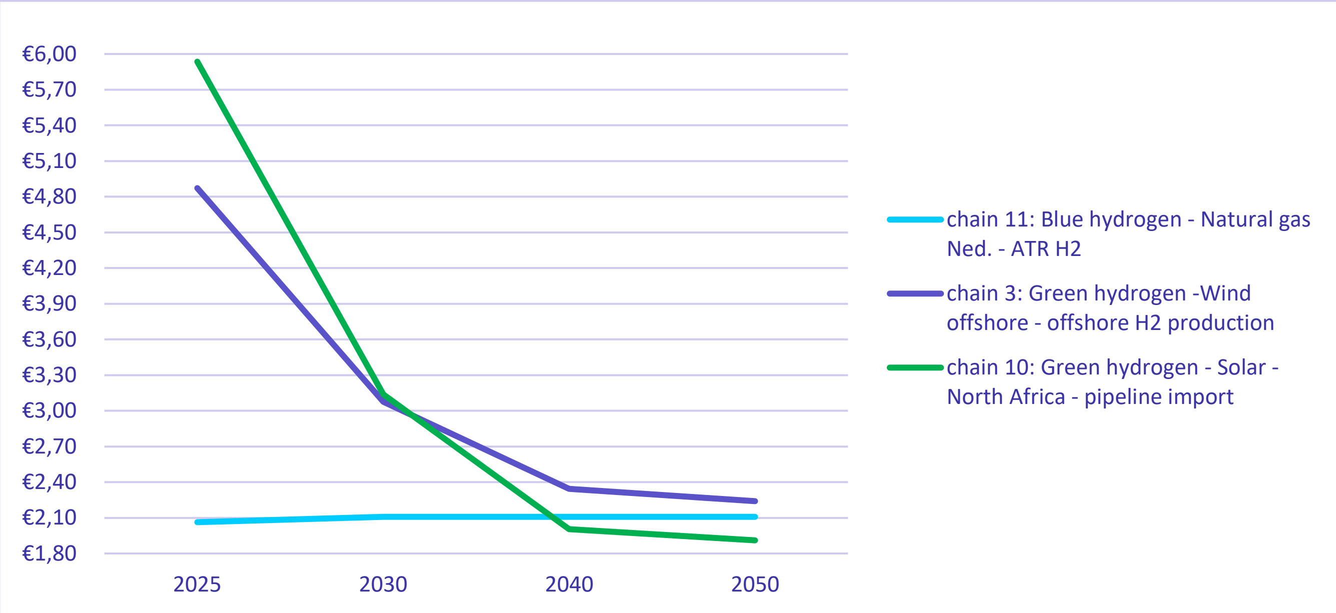


Figure 37 "Most promising hydrogen chains"

6.4 Potential cost reductions in the development phase of hydrogen chains

Zooming in on the two green hydrogen chains explained in the previous paragraph (sun & wind), Figure 38 shows the chain parts that denominate the overall price for hydrogen per kilogram.

It can be concluded that in general the following two chain parts denominate the commodity price of hydrogen:

1. Electrolysers costs (wind chain: €1,15 & solar chain: €1,63) and
2. The costs to produce green electricity (wind chain: €1,47 & solar chain: €0,57).

So in order to cut down the overall costs for 1 kg of hydrogen by 2030, the focus should be on driving down the prices for electrolysers and the production of clean energy. With current parameters it predicts the prices for 1 kg of hydrogen to be €3,08 (wind chain) and €3,14 (solar chain) by 2030. More information about the methodology and parameter details behind these graphs are presented in appendix VIII.

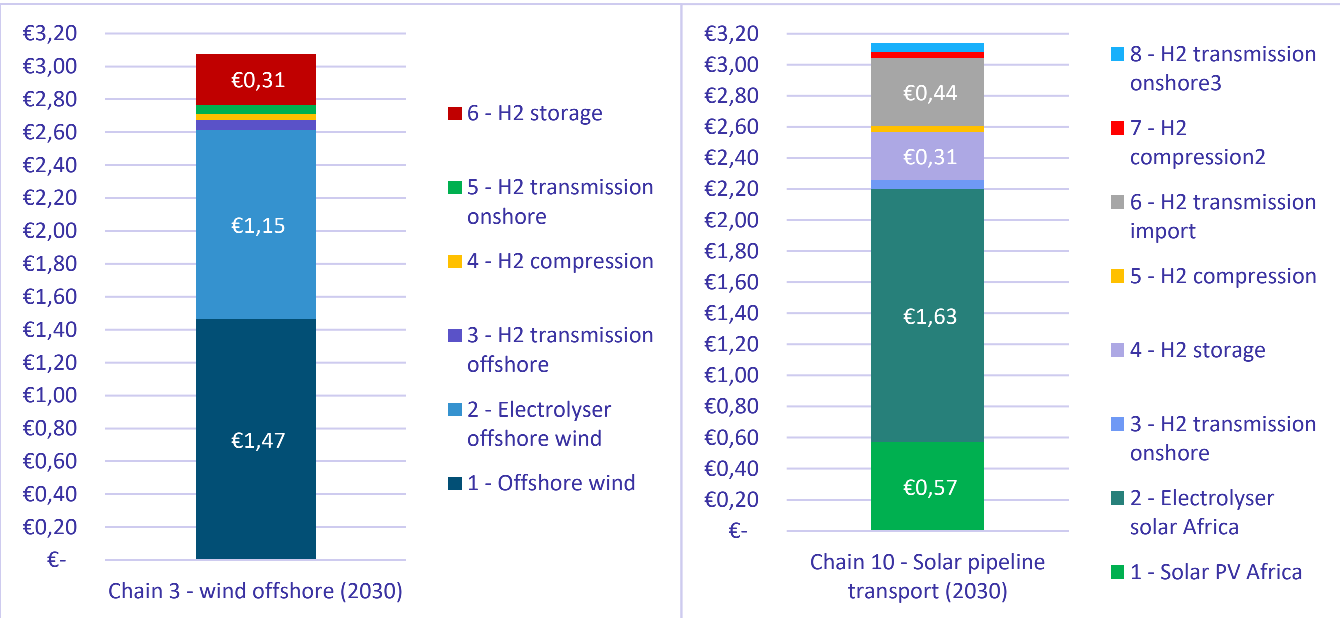


Figure 38 "accumulated chain costs for the 2 cheapest '2030 green hydrogen chains"

6.4.1 Lowering the costs of producing clean energy (solar & wind)

In order to drive the costs down it is important to understand what the factors are which determine the overall costs per chain-part. For fossil fuel like natural gas this depends largely on two factors: the operating costs to run the powerplant and the price of the fuel which is burned to create energy. For renewable energy like wind and sun this is different, no fuel needs to be burned to create energy, the costs are determined by the technology itself (e.g. solar technology) and compared to fossil fuels relatively low operating and maintenance costs of the powerplant.

This costs structure of renewable energy is the factor that makes the levelized costs of energy (LCOE: captures the investments costs of building + maintaining a powerplant as well as the operational costs) scale with the costs of the technology. For renewable energy this means that they follow steep learning curves: when the capacity of the powerplant is doubled, the energy costs are cut down by the same amount (Roser, 2020). See Figure 39.

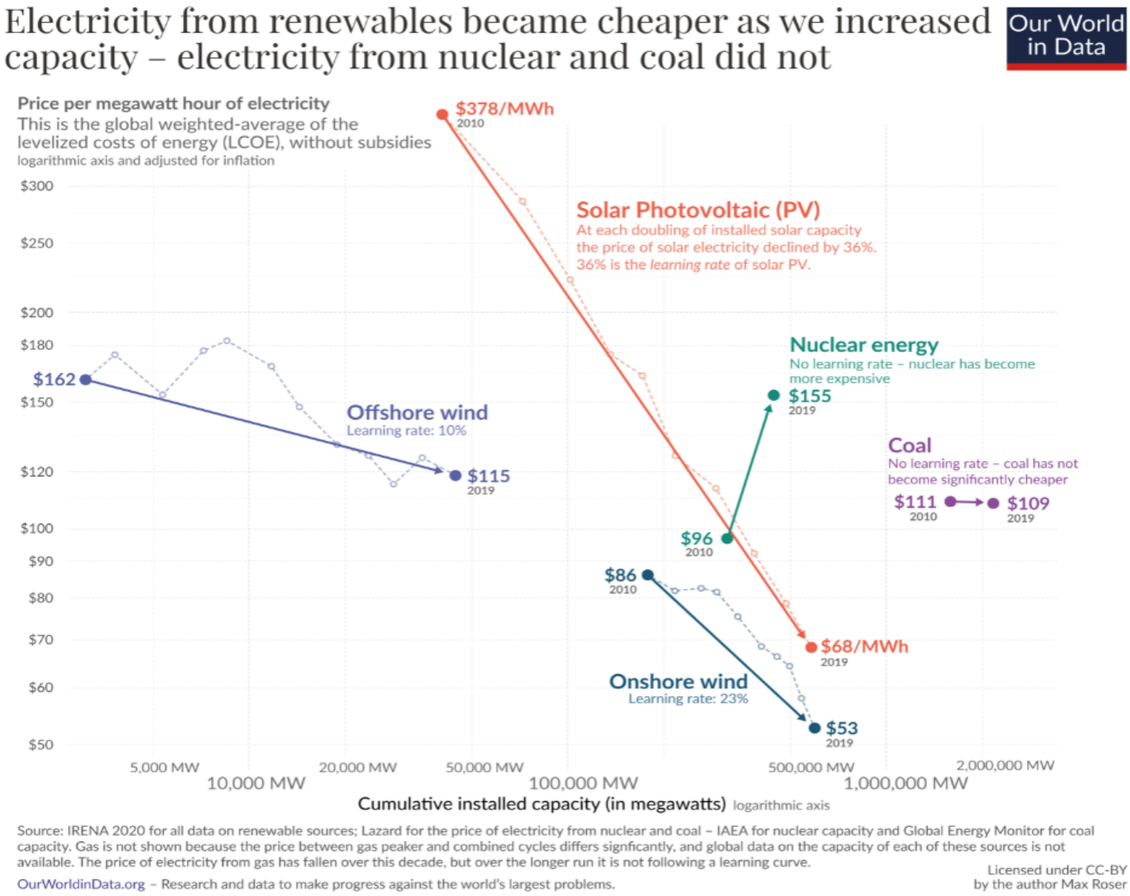


Figure 39 "Learning curves of energy sources in relation to the installed capacity"

6.4.2 Lowering the costs of electrolysers

The previous paragraph explained that economies of scale create steep declining costs for renewable energy. This principle of economies of scale also applies to lowering the costs of electrolysers, the chainpart that gets the upper hand in setting the price for green hydrogen as can be seen in Figure 38. Figure 40 shows that when the fullload hours (capacity of the electrolyser) is increased from 2000 to 8000 the price of hydrogen will go from (in this example): more than 8 $/kg H2 to around $2/kg H2 (IEA, 2019). However, it has been indicated that subsidy is necessary to create this scaling effect. Besides, for the necessary scaling effect of the whole chain, other parts of the chain will also need financial support.

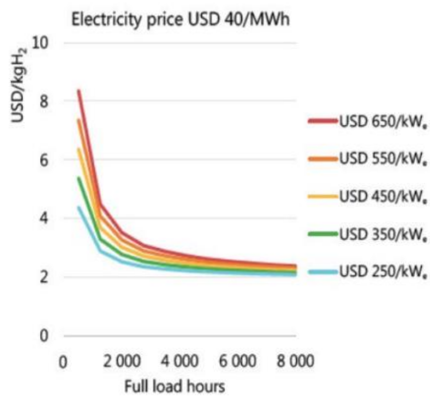


Figure 40 "Cost efficiency opportunities electrolyser"

6.5 Yearly energy prices for a ceramic company when using hydrogen compared to natural gas (2025-2030)

Chapter 6.3 outlined various hydrogen options (€/kg H2) in time related to the source of energy used and the production pathway applied. And chapter 5.6 presented the development of the natural gas price in time taking the CO_2 tax schemes into account for an average ceramic company. This information combined with the volumes that an average ceramic company uses will give insight in the moment in time that hydrogen will become both a sustainable and financial interesting alternative to natural gas for the ceramic industry.

On average 1 kg of hydrogen has the same amount of energy as 4 m^3 natural gas. That implies that an average ceramic industry that used 7 mln m^3 per year needs 1.750.000 kg of hydrogen a year (Visser M. , 2019). Let's assume the same case as Figure 28, but now with a hydrogen forecast and the hydrogen equivalent for natural gas charged with the extra EU-ETS costs. This will imply the following costs for a ceramic company in 2025.

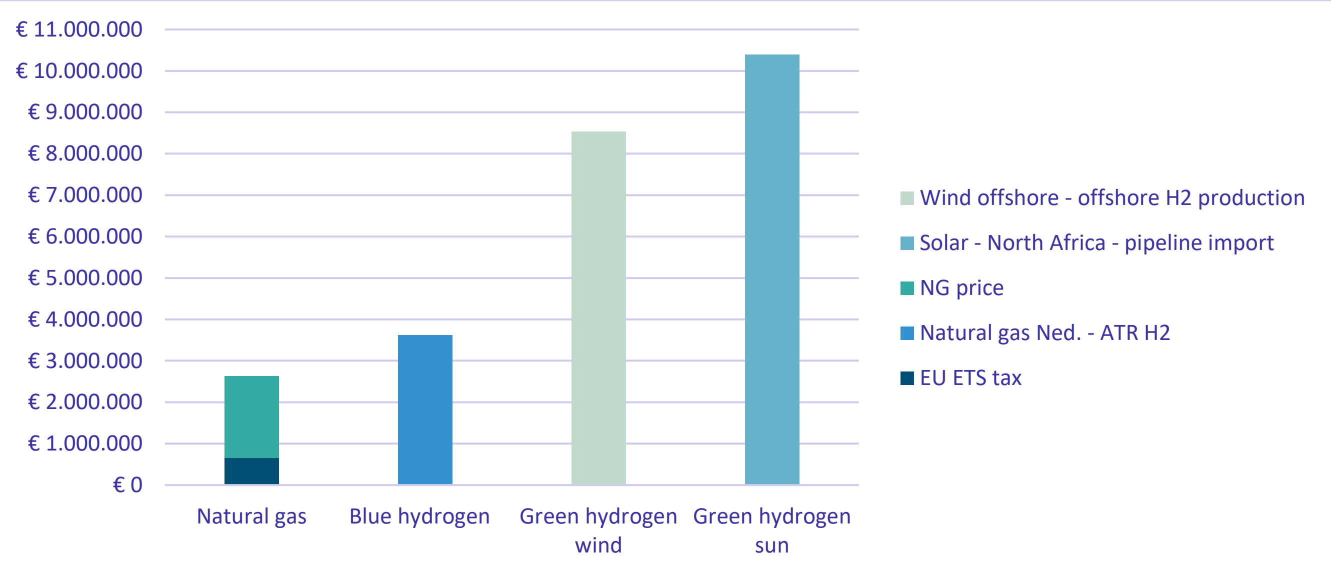


Figure 41 "Cost projection hydrogen & H2 equivalent for natural gas - 2025"

When considering the costs of the EU-ETS system together with the hydrogen equivalent of natural gas it could be stated that in 2025, hydrogen cannot compete with natural gas, even when considered the €116,67 ton/CO_2 EU-ETS tax. As Figure 41 shows, natural gas in 2025 is € €981.741,- cheaper than the cheapest hydrogen variant.

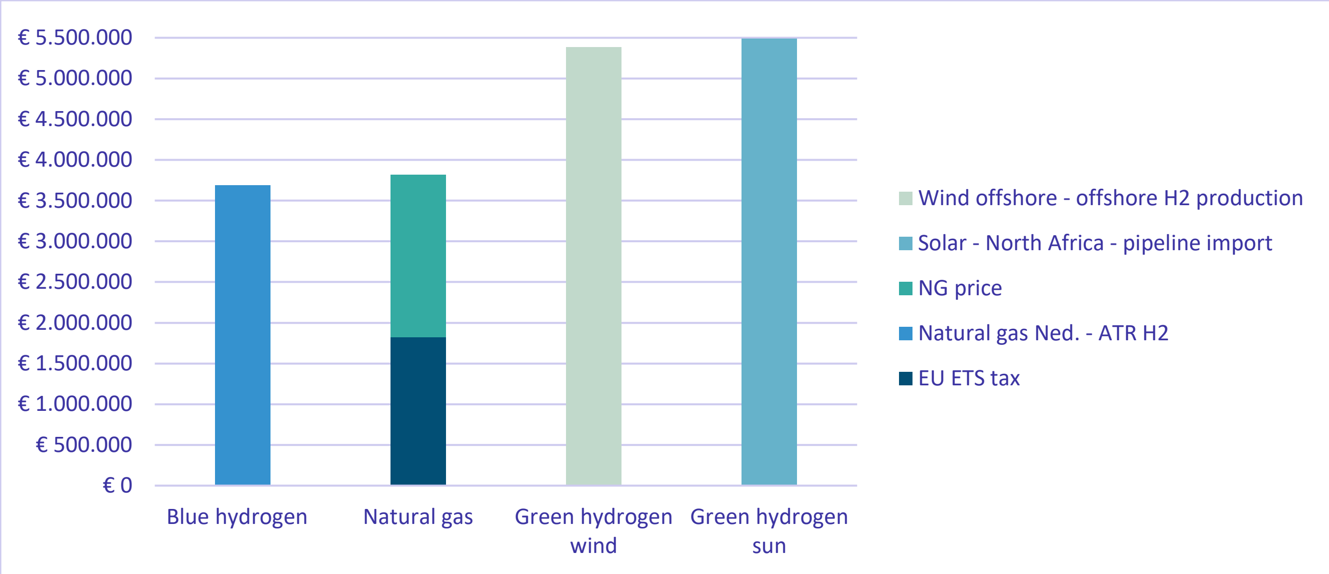


Figure 42 "Cost projection hydrogen & H2 equivalent for natural gas - 2030"

For 2030 an interesting result can be seen. Due to the EU-ETS costs for a ceramic company blue hydrogen can compete with natural gas. Using blue hydrogen will save a ceramic company €130.000,- a year.

As Figure 36 showed, green hydrogen will take at least 8 years longer to become price competitive with natural gas. Which implies that around 2038 green hydrogen will also be a competitive option.

But as stated on page 31, the costs induced by the EU-ETS will double the energy costs for natural gas by 2030. So the figures above still imply that the costs for a ceramic company will double by 2030. Whether they choose hydrogen our natural gas. It is therefore important that cost reduction will follow true as explained in chapter 6.4.

Another option to offer the ceramic industry a realistic transition path is by offering transition subsidiaries. More about this topic is presented in the next chapter.

6.6 Subsidy overview

There are a lot of possibilities with subsidies for sustainability. An overview of the options are outlined in Figure 43. We advise the ceramic industry to consider these options and the possibility to utilize it for: feasibility studies regarding the adoption of hydrogen in their business process or doing pilots with hydrogen kilns or applying for a subsidy to convert necessary other installation to hydrogen.

The downside of the available subsidies is that they all are CAPEX driven. And as the previous chapter concluded, the problem for the industry mostly has to do with OPEX related costs in adapting to a clean source of energy. Because a sector like the ceramic industry has limited options for a clean source of energy, the EU, national or regional government should offer suitable pathways.

Feasebility studies	Pilots	Reaslisation	Operational fase	EU arrangements	Fiscal arrangements
• **Topsector Energy studies industry** • 50% project costs; max €500.000 per project • **small business (MKB) Innovation stimulation Topsectors (MIT)** • 40% costs; max €20.000; budget 5 mill.	• **Demonstration Energy- and climate innocation (DEI+)** • Max 25%; max project timeline 4 year; budget: 108 mill.	• **Accelerated climate investments industry VeKi** • Max 30-50%; CO2 savings and payback longer than 5 years; budget 28 mill • **Subsidy Investments in future-proof Industry (SITI) - Groningen** 10-20% max; min 5 mill.; budget 10 mill. • **National Program Groningen** • Activating H2 activity • Details will follow • **Growth Fund** • Min size 30 mill. • Details Q1 2021	• **Temporarely exploitation support** • Demo -> rollout (klimaatenveloppen 35 mill./year)	• **EU Innovation Fund** • Small scale projects; max 7,5 mill. Capex • **Horizon Europe** • April 2021	• **Tax deduction (EIA)** • 45% deduction of investment costs over the taxable profit

Figure 43 "Overview H2 subsidies for the ceramic industry"

The Dutch government also observed that solely capex driven subsidies do not suffice (government, 2021). In a consultation towards parties that operate in hydrogen chain to produce green hydrogen or built electrolysers, the government checked what government arrangement could help those parties to invest in setting up hydrogen chains. The answers where clear:

"Majority of respondents indicated directly/indirectly, that the operational costs have more priority than support with the investment costs. With other words: an exploitation subsidy makes electrolyser projects in many cases possible, solely an investment subsidy will only be sufficient in some cases."

Original quote (Dutch): "Uit de respons van het overgrote merendeel van de respondenten blijkt direct of indirect dat ondersteuning van operationele kosten meer prioriteit heeft dan ondersteuning van investeringskosten. Met andere woorden: een exploitatiesubsidie maakt elektrolyseprojecten in veel gevallen mogelijk, alleen een investeringssubsidie doet dat slechts in enkele gevallen."

So a majority of the parties indicated that creating instruments to help with operational costs have more priority than instruments for investment costs. The government will now start with the development of the temporarily scale-up instrument. More information regarding this instrument will be published medio 2021, after consultation with the EU commission.

7 Conclusion and recommendations

General conclusions and recommendation

- **General conclusion of this research**
  - Ceramic industry: Electrification is not suitable for the heating process in the ceramic industries. Green Gas is potentially suitable as well, but out of the scope of this research. So far research tells, hydrogen is a suitable energy carrier. The challenges that hydrogen bring are no showstoppers. Yet, more research and experiments are needed on the effects of hydrogen on the product and the burners, the effects on pipelines and required quality of hydrogen. Next to this, a NO_x strategy needs to be developed to control the NO_x emissions. At last, for using hydrogen, it is important to revise the effects on permits and safety
  - Gasunie: Gasunie has a clear role in the sustainable future of the ceramic industry. Therefore, studies like these are important to help the industries towards the use of a more sustainable energy carrier. There are quite some infrastructural opportunities to contribute in this, yet there are several recommendations from this report to get there.
  - The Ministry: This research makes clear that the MInistry needs to facilitate the process of clustering the industries, and the process of decision making of the roles and responsibilities between Gasunie and the regional network operators.

- **General recommendations**
  - 1. Ceramic industry: Researching the possibilities of Green Gas as alternative energy carrier, the effect of hydrogen on the product and materials. Develop a NO_x strategy and revise the effets on permits and safety.
  - 2. Gasunie: increasing pro-activeness when it comes to the development of these studies for the industries to make the connection to the hydrogen backbone. This includes creating different scenario's how to operate for when hydrogen becomes available, which endusers come first, and even thinking about possibilities to bring hydrogen earlier to the enduser. In that perspective, Gasunie should consider if it is necessary to wait until the backbone fully functions
  - 3. The Ministry: facilitating the process of clustering, bringing the parties together (Gasunie, regional network operators, the industries).

Chapter 2 - The bigger picture getting to a climate neutral EU

- **Summary**
  A climate neutral EU is a challenging ambition for all parties to work towards. The required CO2 reduction has its impact on all markets. This chapter showed that the objectives of the Paris climate agreement are challenging for the ceramic sector, yet it is possible to set the first steps towards a more sustainable work practice.

- **Conclusions (applicable for all parties)**
  - The long term 2050 climate goal is set: greenhouse gas emissions should be 95% lower in 2050 than 1990.
  - However, the reduction target for 2030 has shifted recently from 40% to 55%.
  - In the Netherlands we have our Dutch climate agreement in order to meet the 2030 and 50 target.
  - Research has shown that there are four pathways in which the Neterlands can change their current climate agreement.
  - New EU targets based on the 55% from the study of Commission Van Geest are not defined yet, while this study shows what each possible target implies.
  - EU ETS policy will have major impact on the ceramic industry
  - The Dutch CO2 tax will have no influence on the ceramic industry

- **Recommendation**
  - 1. The Ministry: It is an opportunity for the ceramic industry to maintain their business practices when the Netherlands set the same pace as EU policies this. By keeping the same pace, the ceramic industries are able to stay ahead in competition due to the prevention of "carbon leakage". In order to facilitate this, the Ministry is responsible for taking into account the industries in the Netherlands that have to work with the outcome of the EU targets on a national level.

Chapter 3 - Introduction into the ceramic industry

- **Summary**
  Hydrogen is a possible energy carrier vor the ceramic industry and no stopping bariers have been identified. However, research and experiments on burners in combination with the NO_x still needs to be done. Also there is not a clear impact of the impact of using hydrogen on the current permits, pipelines withing the ceramic company and other costs. Even thought it was not part of this research for some individual companies the use of green gas could be a suitable alternative.

- **Conclusions**
  Hydrogen is a possible energy carrier for the ceramic industry and has a number of potential benefits. Such as potential retrofit of existing equipment and reduced impact on the electricity grid.

- **Recommendations**
- 1. Ceramic industry:
  - Doing more extensive research and experiments on larger scale what the effect of hydrogen is on the product. This should also include a description on the needed quality and continious flow of hydrogen since that was not in scope of this research.
  - Doing research and experiments on a larger scale on whether the deployment of a new burner is needed. This should also entail the effects on the NO_x emission. There is currently no information on the the effects of using hydrogen on permits, safety regulations and whether current pipelines within the companies could be re-used. The ceramic industry should take these elements into consideration when changing from natural gas to hydrogen.
  - Doing research whether green gas is a suitable alternative as an energy carrier. For some ceramic companies this could be a possibility.
- 2. Gasunie & ceramic industry: The ceramic industry and Gasunie need to investigate if the supply and demand of hydrogen are corresponding.
- 3. The Ministry: The government should develop a strategy on NO_x emissions and define the requirements per industry. z

Chapter 4 - Infra opportunities for the ceramic industry

- **Summary**

The infra opportunities for the ceramic industry are beneficial: the location of the backbone and the ceramic insdustry is relateively close. When looking into connecting the industry with the backbone, there are multiple opportunities that arise. There are quite some elements that need further research to realize a connection, yet there are rather insightful first steps each party can take to make this happen.

- **Conclusions**
  - The ceramic industry is located nearby the expected hydrogen backbone. In case the industrial clusters can be connected directly to the backbone, the small distance results in costs benefits
  - Three scenario's are suitable for connecting the clusters to the backbone: based on building new infra, based on existing infra, based on a combination of new & existing infra.
  - There are multiple opportunities to handle in order to connect the industry to the backbone. These oportunities vary from defining the place for tie-ins to the backbone, the currently unofficial division of roles between the regional network operators and Gasunie for providing the backbone connection, the corresponding costs, and the availability of other pipelines outside of this analysis.

- **Recommendations**
  - 1. Ceramic industry: The ceramic industry can take the lead by showing potential clusters (examples in this report), unite the sector and present their own strategies and requirtements from important stakeholders. This report is a suitable starting point
  - 2. GTS, regional network operator(s) and the Ministry (parallel to recommendation 1): Research and decision making on the method how industries will be connected to the hydrogen backbone (tie-ins, direct connection points, etc.)
  - 3. GTS & regional network operator(s): In this report it becomes clear that strong collaboration is required between the regional network operators and GTS by comparing their network maps and defining their strategy together to achieve costs benefits for society. Having the potential clusters by the ceramic industry can lead to a deeper analysis by the regional network operators and GTS for their infrastructure opportunities.
  - 4. GTS (parallel to recommendation 2): Proceeding with the investigation and decision making regarding the potentially available pipelines outside of the GTS' and regional operators' network. This can result in cost benefits.

Chapter 5 - A costperspective on natural gas for the ceramic industy

- **Summary**

Historically prices for natural gas have risen. This is mainly due to the increases in VAT and other duties. And these duties will unquestionably rise further till 2030. The climate goals created a drive to lower emissions for serveral industries within the EU including the ceramic industry. A policy created to ensure CO2 reduction is the EU-ETS tax on EU level and the CO2 tax on National level. This tax policy influences the prices of natural gas.

- **Conclusions**
  - There is a widespread in the yearly natural gas costs within the ceramic industry. On average a ceramic company consumes 7 million m^3 of natural gas every year.
  - The ceramic industry is assigned as an EU-ETS industry. This entails that ceramic factories are obliged to pay a CO_2 tax.
  - The EU-ETS tax will have a large impact on the ceramic industry. By 2030 the costs will have almost doubled due to the EU ETS tax (this is excluding the new introduced National tax), because of the shortage in dispensation credits and the growing expense per ton CO_2.
  - According to the current forecast the ceramic industry does not have to pay for the Dutch CO2 tax till 2030.
  - In the ceramic industry, approximately 30% of the final product price consists of energy costs. An average unit product price is around €0,25. By 2030, the energy costs double, and therefore the final product price will be around €0,33: an increase of 32% of the fina product price.

- **Recommendations**
- 1. Ceramic Industry: Calculating more precise CO2 costs, based on the new "Fit For 55" -package from the European Commission. It brings new factors to take into account for a detailed CO2 costs calculation for the ceramic industry. However, changes still can take place based on the translation of this package from the European to the national level.
- 2. Gasunie: Developing an accessible CO2-costs calculator that gives external parties (such as the ceramic industry) insights in their emission costs for the future based on their energy usage and emissions over time.
- 3. The Ministry/EU: consider carefully which further actions are taken for industries like the ceramic industry, as this industry is charged heavily and only has limited options to create a more sustainable business process. Example actions to consider: a quotum to use more 'green' bricks, such as 25% of all bricks for new houses. With not only a focus on producing green bricks, but also via import.

Chapter 6 - A cost perspective on hydrogen for the ceramic industry

- **Summary**

As described in the first chapters, hydrogen is a promising alternative for natural gas. The transport media for hydrogen are discussed (pipelines, trucks, ships), based on distance and volume. We can see three pathways for hydrogen from a costs perspective, and the price differences per colour of hydrogen. This chapter also brings insights in the actions for potential cost reductions and an overview of the current subsidies.

- **Conclusions**
- Transporting hydrogen should be considered in relation to distance and volume.
- There are three potential pathways for adopting hydrogen: blending; 100% hydrogen and going virtual
- The commodity price of hydrogen is between 1,27 and 4,75 per kg of hydrogen by 2030 according to a wide analysis
- The price of green hydrogen is mainly set by the electrolysers and generating renewable energy
- By 2025, hydrogen can still not compete with natural gas, even when considering the EU-ETS tax for the ceramic industry.
- By 2030, blue hydrogen can compete with natural gas.
- Green hydrogen can be price competitive with natural gas around 2038.
- There is a wide spread of subsidy options but they are all CAPEX driven.

- **Recommendations**
  - 1. Ceramic Industry: keeping a close eye on the research developments for changing operational processes to a more sustainable ones (example: the outcome of the DNV research on the burners (Chapter 3)), and consider what costs needed to be made. Together as a sector you can proactively approach the government with this information. This can serve as a starting framework for potential OPEX subsidies.
  - 2. Gasunie: Investigate further the three (or in the future maybe more) pathways for transporting hydrogen to the industries. It would be very relevant to further distinguish the effects of each pathway and give specified advice to the different industries, based on the corresponding volume and distance.
  - 3. The Ministry: Creating subsidies that are OPEX driven instead of CAPEX driven. The main problem for the ceramic industry is finding pathways that are affordable. For this it is important to create OPEX driven subsidies.

8 Appendixes

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II. List of figures

III. The case study Opheusen & Heteren

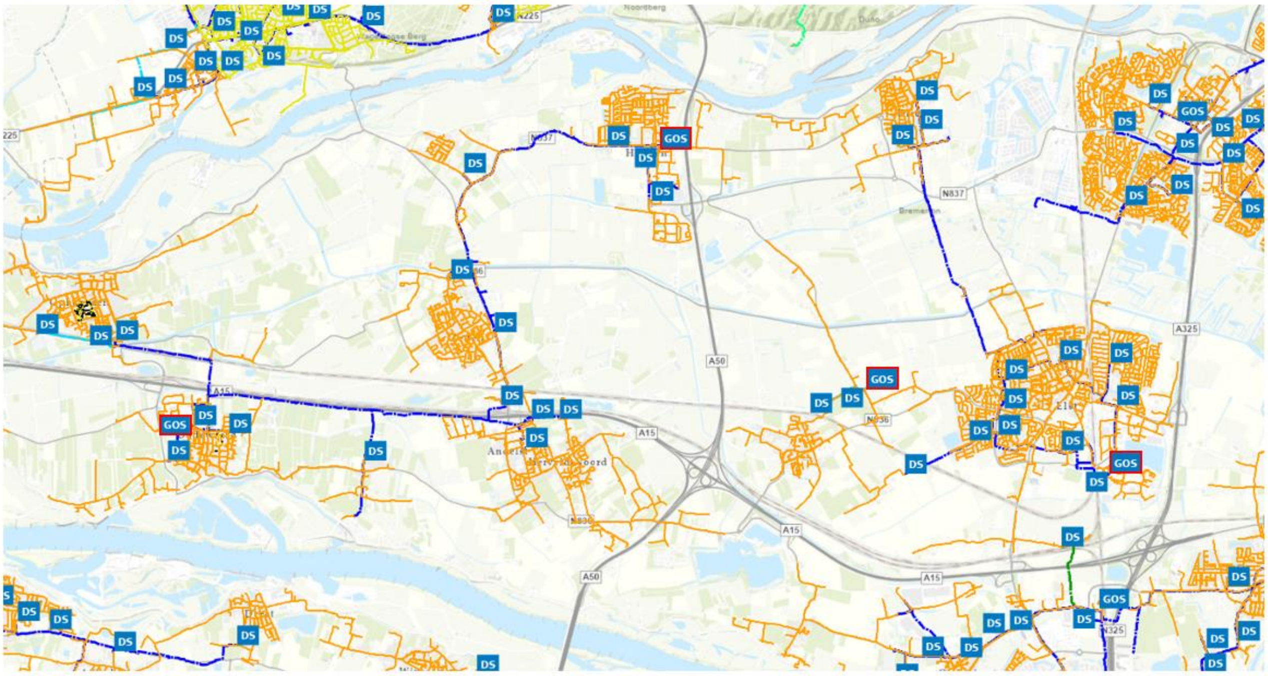
The visualizations are received for this report from Netbeheer Nederland and Liander.

GTS Network

The high-pressure distribution network (8,4.3 bar) of Liander. Here we see that some Gas Receiving Stations, in addition to being linked via the GTS network, are also linked via the Liander network. This offers opportunities for a transition depending on the required capabilities

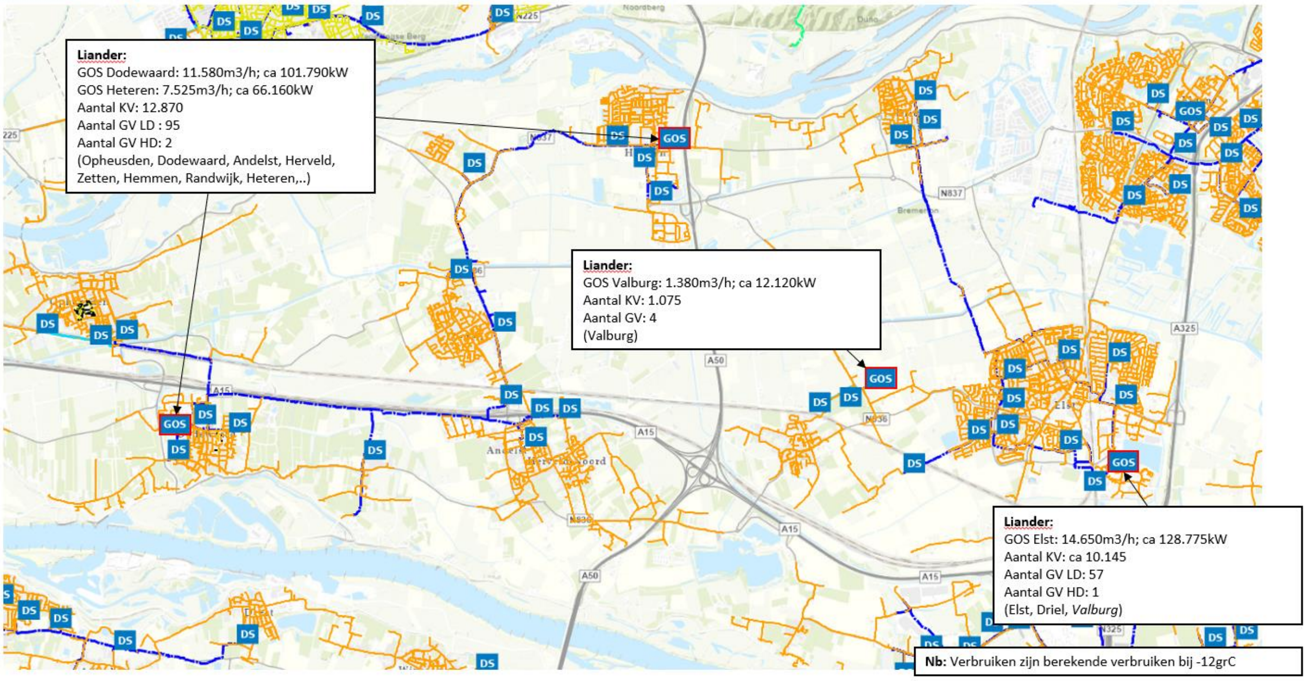
Low-pressure distribution networks of Liander are added to the high-pressure networks. Households, but also some small industry and utilities are connected to these networks. We also see there that the meshed nets are linked between villages. The many district stations (DS) are also shown on the map.

Liander HD gasnet 8bar, 4bar, 3bar en LD gasnet 100mbar, 30mbar

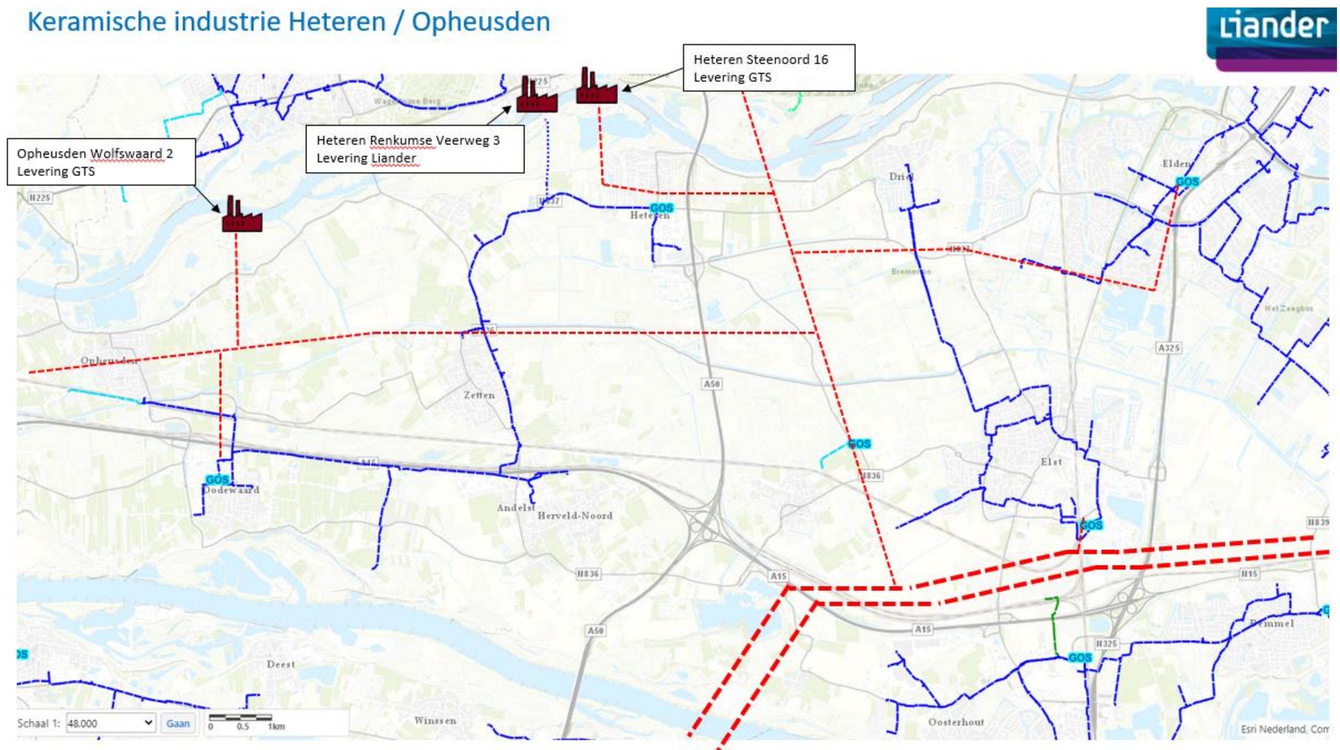


The number of customers shown per GOS as well as the total consumption.

Liander HD gasnet 8bar, 4bar, 3bar en LD gasnet 100mbar, 30mbar



The visualisation below shows the networks of GTS and the high-pressure distribution networks of Liander and the three companies. What is striking is that GOS Valburg is relatively a "small" GOS in terms of number of consumers and cubic meters



Case outcomes

The hydrogen backbone runs under Elst. If the RTL pipeline of GTS is converted to hydrogen, we have three choices at Valburg. GTS lays a new natural gas RTL of three kilometers or Liander lays a new 8 bar pipeline of 1.6 km. The latter has been included in the elaboration because it is cheaper. (This both in terms of distance and the price per meter). Calculations show that Valburg can also be fed in winter via the Liander network from GOS Elst. A third option would be to transfer the 327 KV connections to hydrogen. Central heating boilers are expected to be commercially available in 2027.

If we follow the pipelines, the ceramic factory in Opheusden can be fed without the construction of new infrastructure by cutting a cut in the RTL at Opheusden. The Gos van Opheusden is then supplied from the west. However, because Heteren and Opheusden are linked via Liander's 8 bar network, there is still a degree of security in the event of disruptions to the natural gas supply of Heteren and Opheusden.

Through a second cut south east of Heteren, the GOSs Heteren and Elden can be supplied with natural gas from the north. Then 3.4 km of new pipeline will be needed to supply the two other brick factories with hydrogen. Here's another choice. This is possible with an RTL pipe at 30 or 40 bar. However, because the GOSs have been removed from the RTL, it is probably possible to feed these two customers with 8 bar. The 3.4 km of new pipeline could then be installed at 8 bar, which is much cheaper. This requires a hydrogen GOS to the south east of Heteren. If Valburg is not switched to hydrogen, it may be *possible to switch to an 8 bar network directly at the backbone. This last step has not been calculated since Liander does not have the diameters of the RTL network.*

A next step could be to see whether the industry on the Liander network in the south-west of Heteren can also be switched to hydrogen. This has not yet been calculated.

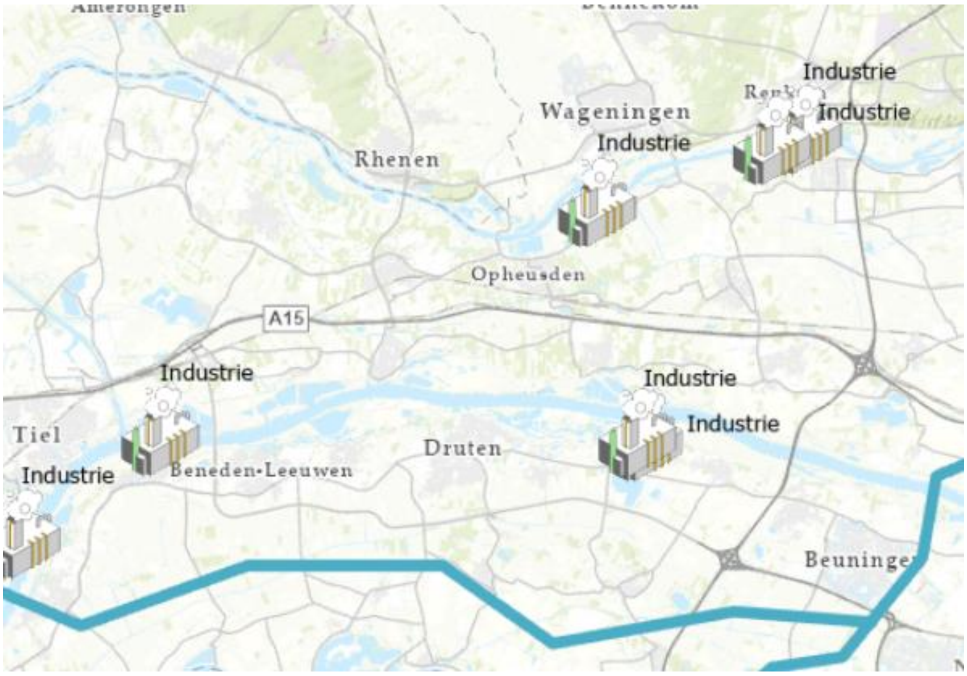
In this case, it appears that three ceramic factories can still be converted to hydrogen fairly separately with a number of steps. However, it also appears that in Valburg, for example, and in the long run perhaps in more places within a corridor of the backbone, it can be logical to convert all connections into one area. In the networks of the regional network operators, various customers are connected to one network. Whereas it is possible to transfer the industry separately on the main GTS networks with parallel pipelines, this is not possible in the more meshed networks of the regional network operators. We can see this as a limitation or as an opportunity. The backbone and the ceramic industry can be a stepping stone to make nearby facilities, small industry, SMEs and the built environment more sustainable in a corridor, provided sufficient green hydrogen is produced.

IV. The industry clusters and expected location of hydrogen backbone

The clusters consist of ceramic industries and ETS companies in the same area that can benefit from collaboration to reduce costs. The blue line is the expected location of the hydrogen backbone.

Cluster 1) Brick Valley

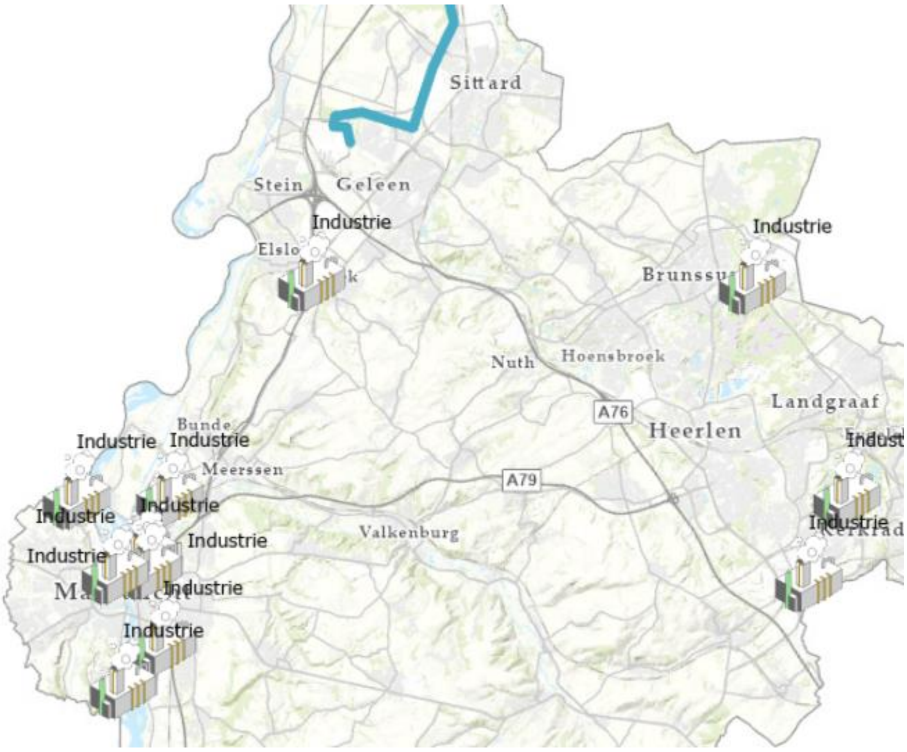
Cluster 2) Wageningen, Tiel.



Cluster 3) Zaltbommel, Engelen, Wijk en Aalburg, Kerkdriel

Cluster 4) Venlo, Reuver, Panningen Helden

Cluster 5) Maastricht, Brunnsum, Kerkrade.



V. Analysis of the ceramic factory emissions and the derived natural gas usage

The Dutch emission authority provides yearly emissions figures of the Dutch EU-ETS companies since 2013. (NEA, 2020). Below in Figure 45, is a subset containing the emissions figures of the EU-ETS companies within the ceramic industry.

To derive the natural gas usages from the CO_2 figures, the methodology in Figure 44 is applied. Details about the natural gas usages of the Dutch ceramic factories is presented in the last 2 columns of Figure 45. There are factories that are marked light grey, they did not report emissions in the last years. This can be due to different reasons.

Cel	Value	Unit	Calculation	Extra info
U3	1	kilotonCO2/jaar	NA	Yearly CO2 emission (1 kilo ton = 1000 ton)
U4	56,6	kgCO2/GJ(OW)	NA	Official established emission factor natural gas based on the lower limit value (source: https://www.rvo.nl/sites/default/files/2020/05/vaststelling-standaard-co2-ef-aardgas-jaar-nationale-monitoring-2020-en-ets-2020-def_0.pdf)
U5	17668	GJ(OW)	"=U2*1000000/U3"	Corresponding natural gas emission
U6	35,17	MJ/m3	NA	Natural gas Groningen upper limit value
U7	31,65	MJ/m3	NA	Natural gas Groningen lower limit value
U8	19632,79911	GJ(BW)	"=U5/U6*U4"	Corresponding natural gas usages (upper limit value)
U9	558225,7353	m3/jaar	"=U7*1000/U5"	Corresponding natural gas usages (upper limit value)
	85%			% of natural gas used by a ceramic factory as a part of the total energy demand (TIKI - DNVGL, 2020, pag. 149)
	16.688		**Natural gas usages ceramic sector GJ(upper limit) based on 1 kton CO2/year**	
	474.492		**Natural gas usages ceramic sector m3/year based on 1 kton CO2/year**	
	So with 1 kton CO2 a year, a ceramic factory will have a natural gas usages of: 474.492,- m3/year			
		Average natural gas usage large steelcompany = 7.000.000,- m3/year		
		Average usages natural gas large chemical compancy = 12.000.000,- m3/year		

Figure 44 "Methodology to convert the CO_2 emission to natural gas consumption"

Company name	City	Emissions 2013 ton/year	Emissions 2014 ton/year	Emissions 2015 ton/year	Emissions 2016 ton/year	Emissions 2017 ton/year	Emissions 2018 ton/year	Emissions 2019 ton/year	Emissions 2019 kton/year	Derived natural gas usages 2019 (BW-GJ)	Derived natural gas usages 2019 (BW-m3/jaar)
B.V. Steenfabriek Huissenswaard	ANGEREN	16.832	20.948	21.788	21.585	21.261	22.438	21.491	21	358.639	10.197.305
Wienerberger B.V. Steenfabriek Bemmel	HAALDEREN	4.659	4.868	5.909	5.438	5.403	5.526	5.732	6	95.655	2.719.787
Steenindustrie Strating B.V.	OUDE PEKELA	4.206	4.786	4.414	4.321	4.832	5.482	6.048	6	100.928	2.869.727
Kleiwarenfabriek Joosten Kessel BV	KESSEL	6.920	7.449	7.245	7.001	8.057	8.677	9.679	10	161.522	4.592.607
Monier Tegelen	TEGELEN	10.515	10.467	10.550	11.091	10.676	10.273	10.765	11	179.645	5.107.905
Wienerberger B.V. Steenfabriek Kijfwaard Oost	PANNERDEN	8.851	9.102	12.211	11.990	12.217	11.872	13.167	13	219.729	6.247.635
Wienerberger B.V. Steenfabriek Kijfwaard West	PANNERDEN	21.753	23.071	22.440	24.290	23.357	24.362	24.668	25	411.657	11.704.766
Wienerberger Dakpannenfabriek Janssen Dings	TEGELEN	10.823	10.071	11.634	11.478	11.818	10.633	11.074	11	184.802	5.254.523
Wienerberger Dakpannenfabriek Narvik Tegelen	TEGELEN	6.903	8.283	9.126	8.499	9.171	8.607	8.778	9	146.486	4.165.090
Kleiwarenfabriek De Bylandt B.V.	TOLKAMER	31.028	31.808	32.958	34.056	33.542	34.713	32.564	33	543.424	15.451.353
Rodruza - Steenfabriek Zandberg BV	GENDT	10.218	11.476	13.483	13.611	13.801	14.240	14.772	15	246.513	7.009.194
Wienerberger B.V. Steenfabriek de Nijverheid	ZALTBOMMEL	13.319	15.318	20.172	20.723	19.781	18.740	17.175	17	286.614	8.149.398
Wienerberger Dakpannenfabriek Narvik Deest	DEEST	8.313	8.048	8.143	7.996	7.754	8.982	6.246	6	104.232	2.963.676
Wienerberger B.V. Steenfabriek Erlecom	ERLECOM	11.003	16.263	15.666	14.797	15.012	14.919	14.732	15	245.846	6.990.214
Steenfabriek Engels Oeffelt BV	OEFFELT	10.958	13.626	13.532	14.149	14.909	15.376	15.009	15	250.468	7.121.649
Wienerberger B.V. Steenfabriek Heteren	HETEREN	7.995	7.826	9.030	8.174	8.874	8.648	9.226	9	153.962	4.377.662
B.V. Steenfabriek Spijk	SPIJK	25.851	24.732	24.782	28.453	25.447	26.602	26.555	27	443.147	12.600.132
Koninklijke Mosa B.V., locatie Vloertegel	MAASTRICHT	14.777	13.826	11.788	11.830	12.368	13.556	12.058	12	201.222	5.721.423
Koninklijke Mosa BV, locatie Wandtegel	MAASTRICHT	20.500	19.619	18.536	19.601	21.995	21.433	20.904	21	348.843	9.918.778
Wienerberger B.V. Steenfabriek Wolfswaard	OPHEUSDEN	9.347	8.972	14.359	14.834	14.925	13.695	14.849	15	247.798	7.045.730
B.V. Steenfabriek Hedikhuizen	HEDIKHUIZEN	12.017	14.511	15.382	14.980	13.420	16.005	14.611	15	243.827	6.932.801
Steenfabriek Gebroeders Klinkers BV	MAASTRICHT	7.588	7.912	8.652	8.756	8.550	8.886	9.223	9	153.912	4.376.239
Monier Woerden	WOERDEN	9.895	9.495	10.850	10.359	11.368	12.271	12.920	13	215.607	6.130.435
Wienerberger B.V. Steenfabriek Schipperswaard	ECHTELD	433	4.643	4.857	5.148	7.911	8.617	9.383	9	156.582	4.452.157
Wienerberger B.V. Steenfabriek Haaften	HAAFTEN	12.586	16.996	14.597	11.477	13.612	16.341	16.552	17	276.218	7.853.790
Gouda Refractories BV	GOUDA	8.278	5.924	10.151	7.855	9.012	9.629	10.481	10	174.906	4.973.149
Kleiwarenfabriek Buggenum BV	BUGGENUM	4.891	-	-	-	-	-	-	NA	NA	NA
Kleiwarenfabriek Facade Beek	BEEK	7.139	7.029	7.890	8.477	8.728	8.377	7.524	8	125.560	3.570.077
Kleiwarenfabriek Joosten Wessem BV	WESSEM	7.489	-	-	-	-	-	-	NA	NA	NA
Kleiwarenfabriek Nuth	NUTH	4.417	-	-	-	-	-	-	NA	NA	NA
Rodruza - Steenfabriek Rossum BV	ROSSUM	7.834	12.005	15.563	16.715	15.570	17.724	16.705	17	278.771	7.926.387
Steenfabriek De Rijswaard BV	AALST	25.600	30.341	27.738	33.864	32.218	31.269	34.684	35	578.802	16.457.276
Steenfabriek Engels Helden BV	PANNINGEN	10.661	13.779	16.854	18.001	18.166	18.594	16.832	17	280.890	7.986.647
Steenfabriek Linssen BV	KERKRADE	2.317	2.113	2.455	2.328	2.520	2.825	3.196	3	53.334	1.516.476
Steinzeug-Keramo BV	BELFELD	4.693	2.505	-	-	-	-	-	NA	NA	NA
Wienerberger B.V. Steenfabriek De Vlijt	WINTERSWIJK	8.560	9.241	9.051	8.886	9.145	8.705	8.460	8	141.179	4.014.201
Wienerberger B.V. Steenfabriek Nuance	AFFERDEN	5.409	5.861	6.204	6.317	5.826	5.744	6.072	6	101.329	2.881.115
Wienerberger B.V. Steenfabriek Poriso	BRUNSSUM	15.174	16.630	17.551	14.985	19.766	27.093	24.665	25	411.607	11.703.342
Wienerberger B.V. Steenfabriek Thorn	THORN	6.841	7.730	9.770	11.145	11.664	12.686	13.334	13	222.516	6.326.875
Wienerberger B.V. Steenfabriek Zennewijnen	ZENNEWIJNEN	8.369	8.967	11.977	16.547	14.913	15.466	15.756	16	262.934	7.476.094

Figure 45 "Emission figures of the ceramic industry 2013 – 2019"

VI. Forecasted transaction price; consumption and costs of natural gas 2020-2030

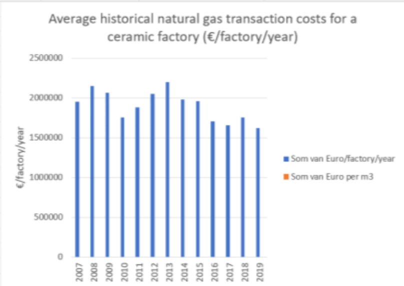
5.4 What EU-ETS CO2 tax means for a ceramic company in the coming years?

Values	Value	Sources:
Values in the table below: tab "CO2 heffing EU NL door KNB"		Sector association for Dutch Ceramics
ceramic emissions increase with 2% a year	2%	Sector association for Dutch Ceramics
Natural gas usages inceases with 2% a year	1,02	Corresponding with the increase in emissions per year
heat emissions 0,8%	80%	Cluster 6 rapport pag. 18: klimaattransiatie door de Nederlandse industrie - Het zesde cluster. De plannen van 9 sectoren
process emissions 0,2%	20%	Cluster 6 rapport pag. 18: klimaattransiatie door de Nederlandse industrie - Het zesde cluster. De plannen van 9 sectoren
current spotprice 1 ton CO2 (6 may 2021) 50 eur	€ 50	https://www.eex.com/en/market-data/environmental-markets/spot-market

Forcasted natural gas costs per year for an average ceramic company 2021-2030

Prijscompor Transactieprijs

Rijlabels	Som van Euro/factory/year	Som van Euro per m3
2007	€ 1.955.223	€ 0,28
2008	€ 2.148.013	€ 0,31
2009	€ 2.065.529	€ 0,30
2010	€ 1.757.510	€ 0,25
2011	€ 1.881.358	€ 0,27
2012	€ 2.053.957	€ 0,29
2013	€ 2.197.749	€ 0,31
2014	€ 1.981.323	€ 0,28
2015	€ 1.961.133	€ 0,28
2016	€ 1.706.789	€ 0,24
2017	€ 1.654.344	€ 0,24
2018	€ 1.755.540	€ 0,25
2019	€ 1.619.627	€ 0,23
Eindtotaal	**€ 24.738.094**	**€ 3,53**



Year	Forecasted natural gas consumption (m3)	Natural gas transaction costs per m3 (EEX, 2021)	Natural gas costs per year for an average factory	Forecast details
2007		€ 0,28		
2008		€ 0,31		
2009		€ 0,30		
2010		€ 0,25		
2011		€ 0,27		
2012		€ 0,29		
2013		€ 0,31		
2014		€ 0,28		
2015		€ 0,28		
2016		€ 0,24		
2017		€ 0,24		
2018		€ 0,25		
2019		€ 0,23		
2020	7.000.000	€ 0,22	€ 1.572.353,15	
2021	7.140.000	€ 0,27	€ 1.956.062,99	Forecast assumptions: see tab "Forecast transaction prices NG". Calculated with the Excel forcastfunction "voorspellingblad" confidence of 95%, upperlimit is used to correct for external influences like closure of the Dutch gasfields (Groningen) which wil likely create higher transactions costs for gas
2022	7.282.800	€ 0,27	€ 1.962.977,39	
2023	7.428.456	€ 0,27	€ 1.969.406,99	
2024	7.577.025	€ 0,26	€ 1.975.329,87	
2025	7.728.566	€ 0,26	€ 1.980.723,45	
2026	7.883.137	€ 0,25	€ 1.985.564,44	
2027	8.040.800	€ 0,25	€ 1.989.828,83	
2028	8.201.616	€ 0,24	€ 1.993.491,91	
2029	8.365.648	€ 0,24	€ 1.996.528,16	
2030	8.532.961	€ 0,23	€ 1.998.911,33	

Figure 46 "Methodology and calculation output of the focasted natural gas: price; consumption and costs"

Figure 46 outlines the calculation method; parameters and outcomes of the linear forecasted transaction price; consumption and yearly costs per factory till 2030.

Figure 47 presents the outcome of the modeled natural gas transaction prices with different confidence intervals. Subsequent analysis in this chapter will be based on the forecasted natural gas transaction price with the highest confidence interval (last column the table of Figure 47)

Year	Natural gas transaction costs per m3	Forcast confidence interval 95%(Natural gas transa	Lowest confidence interval (Natural gas transaction costs per m3)	Highest confidence interval (Natural gas transaction costs per m3)
2007	€ 0,28			
2008	€ 0,31			
2009	€ 0,30			
2010	€ 0,25			
2011	€ 0,27			
2012	€ 0,29			
2013	€ 0,31			
2014	€ 0,28			
2015	€ 0,28			
2016	€ 0,24			
2017	€ 0,24			
2018	€ 0,25			
2019	€ 0,23			
2020	€ 0,22	€ 0,22	€ 0,22	€ 0,22
2021		€ 0,23	€ 0,18	€ 0,27
2022		€ 0,22	€ 0,18	€ 0,27
2023		€ 0,22	€ 0,17	€ 0,27
2024		€ 0,21	€ 0,17	€ 0,26
2025		€ 0,21	€ 0,16	€ 0,26
2026		€ 0,20	€ 0,16	€ 0,25
2027		€ 0,20	€ 0,15	€ 0,25
2028		€ 0,19	€ 0,15	€ 0,24
2029		€ 0,19	€ 0,14	€ 0,24
2030		€ 0,19	€ 0,14	€ 0,23

Figure 47 "Linear forecasted transaction prices of natural gas with different confidence intervals"

VII. Methodology and details behind the hydrogen chain analysis.

In order to determine the commodity price for hydrogen, a simulation model has been developed by Gasunie and reviewed by TenneT and NBNL. Within the model different chains can be composed based on different energy sources; locations of production and transport mediums. In general, the following remarks have to be considered with this simulation model:

1. All hydrogen value chain elements have been calculated in a relativelively simple way, detailed calcualtions are needed for more precise outcomes
2. All energy units are expressed in kilogram of hydrogen equivalent
3. For each chain element a basic set of costs are calculated: CAPEX, OPEX, fuel costs and conversion efficiency
4. By linking the chain elements in a correct way, the total costs along the chain can be calculated
5. All economies of scale are taken in the input parameters of CAPEX and OPEX (possibly resulting in large value differences), NOT in the calculations
6. Input parameters are based on public sources
7. Some chain elements are used in several places, but with different input parameters (e.g. import and export terminal), they have separate tabs
8. All calculations are linear, so for sake of simplicity, often a small standard production unit is used (1 kW(H2) production, 1 kgH2 of ship volume).

The following sources have been used to determine the input parameters:

Study/source	Used for	Weblink
HyChain 2	Many	https://ispt.eu/publications/si-20-06-hychain-2-import-model/
TNO Midden study	H2-boiler costs	https://www.pbl.nl/en/publications/decarbonisation-options-for-the-dutch-sugar-industry
Jacobs	Many	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760479/H2_supply_chain_evidence_-_publication_version.pdf
DNVGL GIE	Many	https://www.gie.eu/index.php/gie-publications/studies
CEGP	Production costs natural gas	https://www.researchgate.net/publication/329950542_The_impact_of_US_LNG_on_Russian_export_policy

Figure 48 "Input sources hydrogen simulation model"

The chains that are simulated and the components of which the chains are composed off, are presented in Figure 49. In Figure 50 you will find an overview explanation of the chain numbers.

	chain part 1	chain part 2	chain part 3	chain part 4	chain part 5	chain part 6	chain part 7	chain part 8	chain part 9	chain part 10	chain part 11	chain part 12	chain
chain 1	Solar PV Africa	Electrolyser solar Africa	H2 transmission onshore	H2 storage	H2 liquefaction	LH2 export terminal	LH2 shipping	LH2 import terminal	LH2 gasification	H2 transmission onshore	H2 compression	H2 storage	
chain 2	Offshore wind	ACDC offshore	E DC cable	ACDC onshore	Electrolyser offshore wind	H2 transmission onshore	H2 compression	H2 storage					
chain 3	Offshore wind	Electrolyser offshore wind	H2 transmission offshore	H2 compression	H2 transmission onshore	H2 storage							
chain 4	Onshore wind	Electrolyser onshore wind	H2 transmission onshore	H2 compression	H2 storage								
chain 5	Solar PV Africa	Electrolyser solar Africa	H2 transmission onshore	H2 storage	NH3 production	NH3 export terminal	NH3 shipping	NH3 import terminal	NH3 cracking	N2H2 separation	H2 compression	H2 transmission onshore	
chain 6	Solar PV NL	Electrolyser solar NL	H2 transmission onshore	H2 storage	H2 industrial boiler								
chain 7	CH4 other	ATR production	NH3 production	NH3 export terminal	NH3 shipping	NH3 import terminal	NH3 cracking	N2H2 separation	H2 compression	H2 transmission onshore			
chain 8	CH4 other	ATR production	H2 liquefaction	LH2 export terminal	LH2 shipping	LH2 import terminal	LH2 gasification	H2 transmission onshore	H2 compression				
chain 9	CH4 NL	SMR production	H2 transmission onshore	CH4 CO2 emission costs									
chain 10	Solar PV Africa	Electrolyser solar Africa	H2 transmission onshore	H2 storage	H2 compression	H2 transmission import	H2 compression	H2 transmission onshore					
chain 11	CH4 NL	ATR production	H2 transmission onshore										
chain 12	CH4 NL	CH4 CO2 emission costs											
chain 13	E grid NL	Electrolyser grid											

Figure 49 "simulated hydrogen chains and their corresponding chain parts"

The input values that have been used to do the calculations per chainpart can be provided on request. For the two chains: “Solar – North Afirca – pipeline import” and “Wind offshore – offshore H2 production, chapter 6 included more detailed analysis of the chain parts. The input parameters for these two chains are presented in Figure 51

Solar - North Africa - liquefaction	chain 1
Wind offshore - onshore H2 production	chain 2
Wind offshore - offshore H2 production	chain 3
Wind onshore - onshore H2 production	chain 4
Solar -North Africa - Ammoniak	chain 5
Solar NL	chain 6
Natural gas in Russia/Norway - ATR H2 - ammonia	chain 7
Natural gas in Russia/Norway - ATR H2 -liquefaction	chain 8
Natural gas Ned. - SMR H2	chain 9
Solar - North Africa - pipeline import	chain 10
Natural gas Ned. - ATR H2	chain 11
Natural gas Ned (including CO2)	chain 12
Electricity Ned	chain 13

Figure 50 "Chain numbers & explanation"

2025	2030	2040	2050	Chain element	Cost element or parameter	Unit
8%	8%	8%	8%	General	WACC	
25	25	25	25	General	Lifetime	year
20	20	20	20	General	Ship visits export terminal	#/year
50	50	50	50	General	Ship visits import terminal	#/year
40	40	40	40	General	Electricity price (@export)	€/MWh
50	50	50	50	General	Electricity price (@import)	€/MWh
20	20	20	20	General	Methane gas price (NL)	€/MWh_HHV
5	5	5	5	General	Methane gas price (production countries)	€/MWh_HHV
390	390	390	390	General	Diesel price	€/ton(diesel)
0,12%	0,12%	0,12%	0,12%	General	Methane leakage whole CH4-chain (NL)	%
1,7%	1,7%	1,7%	1,7%	General	Methane leakage whole CH4-chain (other countries)	%
3000	3000	3000	3000	General	Shipping distance (one-way)	km
3000	3000	3000	3000	General	Long distance pipeline import	km
8000	8000	8000	8000	General	Long distance pipeline import loadfactor	hours/year
200	200	200	200	General	Pipeline distance (NL onshore transmission)	km
200	200	200	200	General	Cable/pipeline distance (NL offshore)	km
125	200	200	200	General	CO_2 price	€/tCO_2
300	200	100	0	General	Emission factor electricity system	grCO_2/kWh(e)
203	203	203	203	General	Emission factor methane system (without green gas)	grCO_2/kWh(CH4_LHV)
3,7	3,7	2,0	1,0	General	Emission factor diesel system	kgCO_2/kg(diesel)
896	350	350	350	Solar PV	CAPEX	€/kW(e)
1%	1%	1%	1%	Solar PV	OPEX fixed	%/year of CAPEX
2500	2500	2500	2500	Solar PV	Loadfactor (Africa)	hours/year
900	900	900	900	Solar PV	Loadfactor (NL)	hours/year
0	0	0	0	Solar PV	Fuel use	kWh(e)/kWh(e)
100%	100%	100%	100%	Solar PV	Conversion efficiency	%
1160	663	250	250	Elektrolyser	CAPEX	€/kW(e)
2%	2%	2%	2%	Elektrolyser	OPEX fixed	%/year of CAPEX
52,5	50	48	47	Elektrolyser	Conversion efficiency	kWh(e)/kgH2
0	0	0	0	Elektrolyser	Outside elektricity use	kWh(e)/kgH2
0,0003	0,0003	0,0003	0,0003	H2 transmission	CAPEX - 6"/16"/48" (1000/10000/100000++ kgH2/hour)	€/kW/m
0,50%	0,50%	0,50%	0,50%	H2 transmission	OPEX	%/year of CAPEX
100%	100%	100%	100%	H2 transmission	Conversion efficiency	
4000	4000	4000	4000	H2 transmission	Loadfactor pipeline	hours/year
1180	1180	1180	1180	H2 compression	CAPEX - 1 MW(e) (1000 kgH2/hour)	€/kW(e)
4%	4%	4%	4%	H2 compression	OPEX	%/year of CAPEX
0,01	0,01	0,01	0,01	H2 compression	OPEX - fuel (30->50, 10->50 bar)	kWh(e)/kWh(H2)
100%	100%	100%	100%	H2 compression	Conversion efficiency	
4000	4000	4000	4000	H2 compression	Loadfactor compression	hours/year
1800	1500	1500	1500	Offshore wind	CAPEX	€/kW
3,20%	1,80%	1,80%	1,80%	Offshore wind	OPEX	%/year of CAPEX
4500	4500	4500	4500	Offshore wind	Loadfactor	hours/year
100%	100%	100%	100%	Offshore wind	Conversion efficiency	
0	0	0	0	Offshore wind	Fuel use	kWh(e)/kWh(e)
0,77	0,33	0,33	0,18	H2 storage	CAPEX	€/kWh(H2_HHV)
2%	2%	2%	2%	H2 storage	OPEX	%/year of CAPEX
20	20	20	20	H2 storage	Energy use compression (67->180 bar)	kW(e)/MW(H2_HHV)
20%	20%	20%	20%	H2 storage	Relative part of hydrogen stored (kg_stored/kg_used)	%
1	1	2	2	H2 storage	Number of cycles per year	
100%	100%	100%	100%	H2 storage	Conversion efficiency	%
8760	8760	8760	8760	General	Loadfactor grid power	hours/year
100%	100%	100%	100%	General	Conversion efficiency electricity grid NL	%

Figure 51 "input parameters"

Output (€/kgH2-eq) of the simulation model for 2025; 2030; 2040 and 2050 for every chain is presented in Figure 52. The corresponding graphs are pictured in chapter 6.3.

€/kgH2-eq	2025	2030	2040	2050
chain 12: Natural gas Ned (including CO2)	€ 1,70	€ 2,25	2,2	2,2
chain 11: Blue hydrogen - Natural gas Ned. - ATR H2	€ 2,06	€ 2,11	2,1	2,1
chain 7: Natural gas in Russia/Norway - ATR H2 - ammonia	€ 3,45	€ 3,57	3,3	3,0
chain 9: Natural gas Ned. - SMR H2	€ 3,51	€ 4,72	4,7	4,7
chain 3: Green hydrogen -Wind offshore - offshore H2 production	€ 4,87	€ 3,08	2,3	2,2
chain 2: Wind offshore - onshore H2 production	€ 5,49	€ 3,67	2,9	2,8
chain 10: Green hydrogen - Solar - North Africa - pipeline import	€ 5,94	€ 3,14	2,0	1,9
chain 4: Wind onshore - onshore H2 production	€ 6,64	€ 4,05	2,9	2,8
chain 8: Natural gas in Russia/Norway - ATR H2 -liquefaction	€ 6,74	€ 4,49	3,2	3,0
chain 5: Solar -North Africa - Ammoniak	€ 7,37	€ 4,54	3,1	2,8
chain 1: Solar - North Africa - liquefaction	€ 11,50	€ 5,81	3,2	2,9
chain 6: Solar NL	€ 15,47	€ 7,46	4,2	4,0

Figure 52 "€/kgH2-eq per hydrogen chain for 2025 till 2050"

VIII. Methodology and details behind the cost structure per chain-part of the green hydrogen chains

Output (€/kgH2-eq) of the simulation model for the green hydrogen chains (10-sun & 3-wind) when considering the different parts of the chain and accompanying costs, are presented in Figure 53.

41	**6.4 Potential cost reductions in the development phase of hydrogen chains**								
42									
43	Source	HyWay27 chainmodel developed and maintained by Gasunie							
44	Contactperson for more information input/parameters: Anne-Marijn Kamps								
45									
46	Chain 10: Solar - North Africa - pipeline transport								
47	Chain 3: Wind offshore - Offshore H2 production								
48	Costs per element within the selected chain								
49	Reference year: 2030								
50	Unit measure: €/kgH2-eq								
51									
52	Chain 10 - Solar pipeline transport (2030)	1 - Solar PV Afri	2 - Electrolyser solar Africa	3 - H2 transmission onshore	4 - H2 storage	5 - H2 compressio	6 - H2 transr	7 - H2 compression2	8 - H2 tran
53	**yearly CAPEX**	€ 0,52	€ 1,24	€ 0,06	€ 0,24	€ 0,01	€ 0,41	€ 0,01	€ 0,06
54	**OPEX**	€ 0,06	€ 0,27	€ 0,00	€ 0,05	€ 0,00	€ 0,02	€ 0,00	€ 0,00
55	**Fuel-OPEX**	€ -	€ -	€ -	€ 0,01	€ 0,02	€ -	€ 0,02	€ -
56	**Conversion efficiency**	€ 1,00	€ 0,79	€ 1,00	€ 1,00	€ 1,00	€ 1,00	€ 1,00	€ 1,00
57	**Conversion losses**		€ 0,12	€ -	€ -	€ -	€ -	€ -	€ -
58	**CO2**	€ -	€ -	€ -	€ 0,01	€ 0,00	€ -	€ 0,00	€ -
59	**CO2 due to losses**		€ -	€ -	€ -	€ -	€ -	€ -	€ -
60	**Total**	**€ 0,57**	**€ 1,63**	**€ 0,06**	**€ 0,31**	**€ 0,04**	**€ 0,44**	**€ 0,04**	**€ 0,06**
61	**CAPEX**	€ 5,51	€ 13,26	€ 0,27	€ 12,87	€ 0,12	€ 4,04	€ 0,12	€ 0,27
62	**Capex due to losses**		€ 1,17	€ -	€ -	€ -	€ -	€ -	€ -
63									
64	**kg Co2/kg H2 eq**	CO2 emission	€ -	€ -	€ -	€ 0,03	€ 0,02	€ -	€ 0,02
65									
66	Chain 3 - wind offshore (2030)	1 - Offshore win	2 - Electrolyser offshore win	3 - H2 transmission offshor	4 - H2 compressio	5 - H2 transmission	6 - H2 storag		
67	yearly CAPEX	€ 1,23	€ 0,69	€ 0,06	€ 0,01	€ 0,06	€ 0,24		
68	OPEX	€ 0,24	€ 0,15	€ 0,00	€ 0,00	€ 0,00	€ 0,05		
69	Fuel-OPEX	€ -	€ -	€ -	€ 0,02	€ -	€ 0,01		
70	Conversion efficiency	€ 1,00	€ 0,79	€ 1,00	€ 1,00	€ 1,00	€ 1,00		
71	Conversion losses		€ 0,31	€ -	€ -	€ -	€ -		
72	CO2	€ -	€ -	€ -	€ 0,00	€ -	€ 0,01		
73	CO2 due to losses		€ -	€ -	€ -	€ -	€ -		
74	**Total**	**€ 1,47**	**€ 1,15**	**€ 0,06**	**€ 0,04**	**€ 0,06**	**€ 0,31**		
75	CAPEX	€ 13,12	€ 7,37	€ 0,27	€ 0,12	€ 0,27	€ 12,87		
76	Capex due to losses		€ 2,79	€ -	€ -	€ -	€ -		
77									
78	CO2 emission	€ -	€ -	€ -	€ 0,02	€ -	€ 0,03		
79									
80									
81	Total costs chain 3 - wind offshore (2030)	€ 3,08							
82	Total costs chain 10 - Solar pipeline transport (2030)	€ 3,14							
83									

Figure 53 "Cost structure green hydrogen chain sun and wind per chain-part"

IX. Methodology and calculation details behind the yearly energy prices for a ceramic company when using hydrogen compared to natural gas (2025-2030)

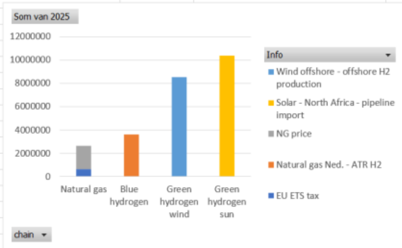
See Figure 54 for more information about the induced costs for a ceramic company when using the different types of hydrogen in 2025 & 2030.

6.5 Yearly energy prices for a ceramic company when using hydrogen compared to natural gas (2025-2030)

Natural gas usage average ceramic company	7.000.000		
1 kg of hydrogen = 4 m3 natural gas	4	m3 natural gas	source: https://twitter.com/bm_visser/status/1172384987561123840
7 mill m3 natural gas is equal to	1.750.000	kg of hydrogen	
Unit measure:	€/kgH2-eq		
Blue hydrogen - total natural gas 2025	€ 343.891,6		
Blue hydrogen - total natural gas 2030	€ 109.652,4		
Green hydrogen - total natural gas 2030	€ 2.423.623,2		

chain	Info	2025	2030	Total natural gas	Total natural gas 2
Natural gas	NG price	€ 1.975.329,9	€ 1.996.528,2	€ 2.629.167,0	€ 3.819.664,9
Natural gas	EU ETS tax	€ 653.837,1	€ 1.823.136,8		
Blue hydrogen	Natural gas Ned. - A	€ 2.973.058,6	€ 3.929.317,4		
Green hydrogen wind	Wind offshore - offs	€ 6.034.719,4	€ 6.243.288,1		
Green hydrogen sun	Solar - North Africa	€ 11.624.186,8	€ 7.080.821,9		

Som van 2025	Kolomlabels					
Rijlabels	**EU ETS tax**	**Natural gas Ned. - ATR H2**	**NG price**	**Solar - North Africa -**	**Wind offshore - offsh**	**Eindtotaal**
Natural gas	653837,1055		1975329,871			2629166,976
Blue hydrogen		3610907,522				3610907,522
Green hydrogen wind					8526348,413	8526348,413
Green hydrogen sun				10387499,48		10387499,48
Eindtotaal	**653837,1055**	**3610907,522**	**1975329,871**	**10387499,48**	**8526348,413**	**25153922,4**



Som van 2030	Kolomlabels					
Rijlabels	**EU ETS tax**	**Natural gas Ned. - ATR H2**	**NG price**	**Solar - North Africa -**	**Wind offshore - offsh**	**Eindtotaal**
Blue hydrogen		3689849,969				3689849,969
Natural gas	1823136,785		1996528,163			3819664,948
Green hydrogen wind					5384529,213	5384529,213
Green hydrogen sun				5492850,779		5492850,779
Eindtotaal	**1823136,785**	**3689849,969**	**1996528,163**	**5492850,779**	**5384529,213**	**18386894,91**

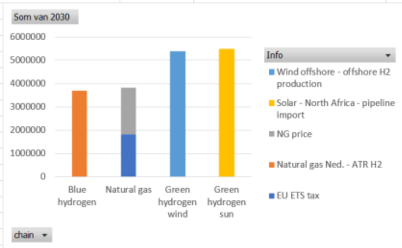


Figure 54 "calculation details behind the costs per type of hydrogen for a ceramic factory (2025-2030)