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HyChain 1

Assessment of future trends in industrial hydrogen demand and infrastructure

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Summary

Objective, scope and approach

The Institute for Sustainable Process Technology (ISPT) has initiated a System Integration program with the main goal of advancing key technical options for process industries, e.g. the development of a gigawatt electrolyser plant for hydrogen production. Within this program HyChain is one of the key projects, in which we, together with various key industrial players in the Netherlands, aim for answering the question: *How can we make an optimization of the full hydrogen value chain to deliver the lowest cost, carbon-neutral hydrogen to Dutch industries, and, which barriers and bottlenecks stand in the way?*

HyChain 1 is the first part from a potentially 5 parts counting HyChain project of which now three are running and two are in the design phase. This study explores the possible future role of hydrogen in different end-use sectors in the Netherlands with a focus on industrial demand. Further, it considers competing energy carriers for decarbonization of various sectors and the subsequent system implications.

The main research question of this project is:

What are the major tipping points influencing the shift from incremental change towards rapid growth in a hydrogen economy, across various sectors?

To answer the research question, we have used a four-step approach:

Literature review (Ch 3)	A literature review is performed on existing, most recent Dutch and international studies. This gives insights into the projected range of hydrogen and contraints, drivers and tipping points.
Hydrogen demand (Ch 4 and 5)	Literature, interviews and a sector-based analysis, are used to produce two extreme scenarios. A high scenario' where hydrogen is the preferred choice and a low scenario; where an alternative to hydrogen is used when possible.
Tipping points (Ch 6)	Based on the interviews, literature and a workshop with industrial partners; the major tipping points explaining the gap between the high and low scenarios are identified and quantified using first part of this study.
System effects (Ch 7)	The scenarios as well as the tipping points are put into a system perspective, which led to identification of new tipping points and system consequences.

Results from the study

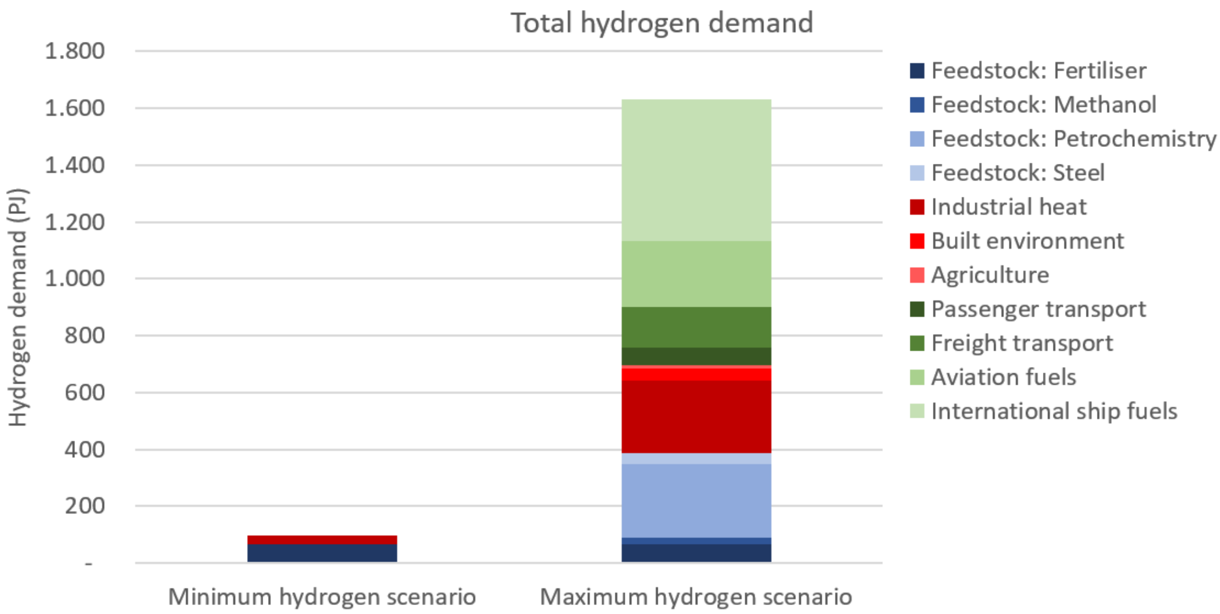
Literature review

- **Major differences in projected demand**
  Our meta-analysis of 18 recently reported studies shows a diverse role of projected hydrogen use in the Netherlands in 2050 ranging from nearly zero to almost 1900 PJ/yr.
- **Major applications**
  - as fuel for dispatchable power generation (up to 380 PJ/yr or 3.2 Mt/yr)
  - as fuel for transport (up to 905 PJ/yr or 7.5 Mt/yr) if hydrogen use for synthetic fuel production for all modes of transport is included)
  - as fuel for high temperature heat in industry (up to 288 PJ/yr or 2.4 Mt/yr)
  - as feedstock for industry (up to 550 PJ/yr or 4.6 Mt/yr)
- **Integrated models needed**
  The complexity of the future role of hydrogen in an integrated system makes the use of optimization and simulation models desirable to obtain a more detailed insight into the different relations and dependences.

Hydrogen demand

Data from the literature review and a series of interviews with stakeholders from the different sectors is used to perform an end-use sector-based analysis. The results from this analysis allow us to estimate hydrogen demand for a minimum and maximum hydrogen scenario. Our assumptions are based on the current energy use, thereby, no growth in energy demand is assumed.

- Minimum H_2 scenario: ~100 PJ/yr (0,8 Mton/yr)
  Hydrogen is only used in the fertilizer industry and to provide a part of high temperature heat. For all other uses, an alternative is identified.
- Maximum H_2 scenario: ~1600 PJ (13 Mton/yr)
  The high scenario shows the maximum possible hydrogen demand based on current energy and feedstock uses. The three major uses of hydrogen are: fuel for international shipping (500 PJ) and industrial heat (255 PJ), and as feedstock for petrochemistry (260 PJ).



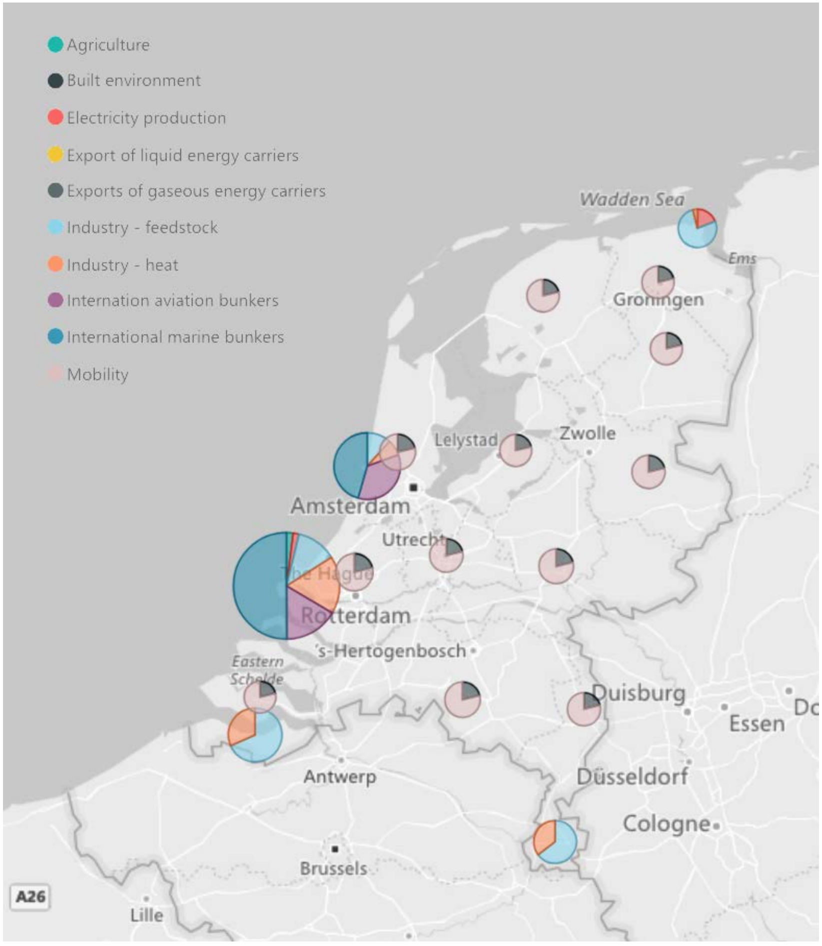
The minimum and maximum hydrogen scenarios reveal a significant difference in total projected hydrogen use (100 to 1600 PJ/yr for respectively the low and high case). Such a large difference is also observed in our literature review (0 to 1900 PJ/yr), which even surpasses the range of our two scenarios, and illustrates the high uncertainty in the projected future role of hydrogen in the Netherlands. We should note that the range of the literature review also covers hydrogen use for dispatchable power supply, an application of hydrogen use that is not covered in our end-use sector-based analysis. Identification and quantification of the major tipping points provides more insight into the origin of this observed wide ranges in hydrogen use.

Tipping points

There are various factors which will influence whether the future demand of hydrogen will follow the trend towards the maximum scenario (1600 PJ/yr) or the minimum scenario (100 PJ). We have identified several *economical* tipping points and quantified their influence on hydrogen demand (depicted between parentheses), such as the availability and costs of offshore wind (640 PJ) and sustainable biomass (1100 PJ), and the performance of electrical storage, e.g. in batteries. *Social and political* aspects can play a substantial role in determining the size and rate of hydrogen uptake by the market. The acceptance of CCS (890 PJ) and safety perception of hydrogen are serious social factors that must be taken into account. Incentives by the government to stimulate green energy and the development of hydrogen technologies within the Netherlands will provide more certainty to overcome financial barriers in the early deployment phase.

System effects

Establishing the range in projected hydrogen use in the Netherlands and identifying and quantifying the major tipping points, provides us a profound basis to investigate the role of hydrogen according to the minimum and maximum scenario from a system perspective. The Energy Transition Model (ETM) is used to illustrate potential hydrogen clusters based on geographical distribution of the domestic hydrogen demand. Industrial hydrogen demand is localized in five main clusters in the Netherlands. Decentralized hydrogen demand for the built environment and mobility can benefit from the large infrastructure needed for the industrial demand.



The ETM simulations show that the uptake of domestic green hydrogen production is not just determined by its competitiveness with import of hydrogen, but likely also by the extent to which large quantities of offshore wind must be integrated into the energy system. The systemic role that molecules play in stabilizing and increasing security of supply suggests that biomass and hydrogen (or related molecular carriers) will play an important role in the future. Which of these will be most prominent is hard to predict, but care should be taken to avoid any partial lock-in of technologies by only striving for short-term emissions reductions.

Potential for domestic renewable power and therefore green hydrogen production is significant, but any scenario with significant hydrogen demand will rely on considerable amounts of imported hydrogen. The domestic green hydrogen production potential depends heavily on the availability of renewable electricity. Since electrification is also a pre-condition for a large installed renewable power generating capacity, the relation between electrification and hydrogen uptake warrants further research.

When considering future flows of hydrogen between clusters of demand and supply it is important to also look at the potential throughput of energy carriers and molecules to the Hinterland, an issue that is not well addressed in an energy system analysis of solely the Netherlands. Rough estimates indicate that additional imports of hydrogen or synthetic molecules at volumes roughly three times the maximum demand scenario for the Dutch market would be required to cover current flows of energy carriers through the Netherlands. Significant effects can also be expected on the supply side if North Sea countries integrate their exploitation of offshore wind resources. Given the current importance of Dutch ports and industry in supplying energy and molecules to neighbouring countries, studying the developments in these countries, especially Germany, is necessary. A low hydrogen demand energy system in the Netherlands would not fit well into a NW Europe that is mostly hydrogen-based and vice-versa. Dutch industry and ports would stand to lose international market share. In addition, technology choices on a global and European level will significantly affect expected cost reductions for these technologies.

Conclusions

Our study reveals that there exists a high level of uncertainty in the projected future use of hydrogen in the Netherlands. In general the Netherlands are well-positioned to deploy a hydrogen economy based on the potential for renewable electricity production on the North Sea, the existing gas infrastructure, and the large industrial and maritime sector. In a maximum hydrogen scenario, a few applications stand out in their projected demand: hydrogen as fuel for aviation, shipping, and industrial heat, and as feedstock for industry. This demand is strongly located in five industrial clusters. Future supply of hydrogen to meet these demands in a competitive manner is influenced by for instance political incentives, the availability and costs of biomass, the acceptance of CCS, the deployment of renewable electricity production, and, probably most important, the emission reduction targets.

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1. Introduction

1.1 Background

The Paris climate agreement has brought all nations together to combat climate change and adapt to its effects. Countries have been actively striving towards a sustainable future. To limit global warming, anthropogenic greenhouse gas (GHG) emissions must be reduced to net zero or negative figures as soon as possible (IPCC, 2018). Combustion of fossil fuels emit CO_2, which is the major contributor of overall GHG emissions. To restrict the use of fossil fuels, a switch to renewable energy sources is imperative. Further, these sources must be linked via climate-neutral energy carriers to fulfil final energy needs of; for instance, built environment, transport sector, and industries. Renewable electricity is a good example of such an energy carrier. One possible solution is electrification of end-use sectors because of which electricity could supply a significant share of renewable energy to society. However, it is highly unlikely that electricity will be the only energy carrier of our future society in an era of increasing urbanization and rapid growing economies. Currently, around 80% of our energy consumption is supplied by fossil hydrocarbon fuels. Also, in most countries, the vast majority of electricity is produced by combustion of fossil hydrocarbons. The Dutch government is still deliberating on: where to invest, and how best to achieve our environmental goals over the upcoming years. Further, many industries are exploring numerous routes to adapt themselves for future reality. How will the share of energy carriers change in the future and what are the alternative energy carriers? Can hydrogen be such an alternative and to what extent?

In this study we have explored the future role of hydrogen as; energy carrier and feedstock for the Netherlands. The prime focus was on industry sector for which potential demand was projected until 2050. Additionally, expected adoption of hydrogen was studied in adjacent sectors: built environment, agriculture and mobility. Further, consequences on system effects and boundaries because of changing energy mix were analysed.

1.2 Current Hydrogen economy

Hydrogen is a clean fuel that does not emit CO2 during combustion. It is used in many different applications, majorly in industry sector.

- **Supply**: In Europe, the Netherlands is second largest producer of hydrogen with an estimated annual volume of more than 10 billion cubic meters or 110 PJ/yr (DNV GL, 2017). Hydrogen is mainly produced by reforming of methane, as by-product of steam cracking of naphtha (olefin synthesis) and by electrocatalytic brine conversion (chlorine production).

- **Infrastructure**: Hydrogen is commonly produced on site for bulk industrial usage. It is also transported through pipelines in various industrial clusters. Globally, total estimated network of large hydrogen pipelines accounts for more than 4500 kms, of which almost 1600 kms is in Europe (H2tools, 2016). Air Products operates the network in Port of Rotterdam which link local and clustered industries (140 kms pipelines). Air Liquide operates network which links the Port of

Rotterdam to the North of France via Belgium, and a separate network in the Ruhr area in Germany (together around 1000 kms of pipelines) (DNV GL, 2017). Recently, industrial sites of Dow and Yara are connected with a 12 kms hydrogen pipeline, operated by Gasunie (Gasunie, 2018b). Previously, this was used to transport natural gas. Hydrogen is also transported by trucks to small-scale industrial customers and increasingly to refuelling stations. Transport occurs either in gaseous form in high pressure cylinders or tubes, or in liquid form in cryogenic tanks (< 253 °C). In principle, hydrogen can also be transported by trains, barges and ships.

Figure 1: Gas grid operated by Air Liquide (red represents hydrogen) (CE Delft, 2018)

- **Demand:** Currently, a large share of total hydrogen demand in the Netherlands is used: as feedstock for production of ammonia and methanol, and, in refineries for desulfurization, hydrogenation and cracking of oil. Various other applications are found in the industrial sector, for instance in industries like chemical, glass manufacturing, metallurgy, welding, and for cryogenic research (FCH2JU, 2019).

1.3 Objective

At present state of technology, hydrogen can be produced sustainably with a low CO2 footprint in two different ways (excluding bio-based route). First, hydrogen can be produced from natural gas by reforming methods in combination with carbon capture and storage (blue hydrogen), and second, it can be produced from (renewable) electricity sources through electrolysis (green hydrogen). In the last decade, interest in electrolysis has revived because the technology is considered as one of the key building blocks of future green yet, reliable energy systems. For example: one of the most attractive features of a green hydrogen production system is that hydrogen can act as a buffer in a supply-driven electricity production system (given that solar and wind energy are variable resources). Furthermore, hydrogen can act as a fuel in transport & mobility as well as raw materials for the industry sector. Additionally, hydrogen could also replace natural gas as heating source in the built environment. Given the transitions currently taking place in our energy and production systems, the demand for hydrogen is anticipated to increase significantly over the upcoming decades. This is not only to meet new chemical industry demands (for example to provide a means for valorising waste carbon into products), but also to fulfil the demand for heat, mobility, and other uses such as enabling Direct Reduction of Iron (DRI) in the steel industry. Study done by ECN[1] estimates a potential demand of hydrogen for all applications of, up to 1700 PJ/a (TKI Nieuw Gas, 2018). This represents more than 50% of current total primary energy consumption of the Netherlands, excluding bunkering and aviation. Finally, given the current role of the Netherlands as an energy hub for Northwest Europe, we must anticipate the role, the Netherlands may continue to fulfil in the new energy system with hydrogen and related liquids/gases.

1.3.1 Energy Carriers and Supply Chain Program

For the aforementioned reasons, working on an understanding of meeting hydrogen demand for industry in the Netherlands requires a value-chain approach. By bringing together (future) users of hydrogen, transport and storage parties, hydrogen producers, energy producers, and strong knowledge partners active in the area of hydrogen, ISPT want to answer the main research question of:

How can we make an optimization of the full hydrogen value chain to deliver the lowest cost, carbon-neutral hydrogen to Dutch industries, and, which barriers and bottlenecks stand in the way?

This question is divided into five separate parts, of which one to three are definitive, four and five are still to be adjusted using the insight of the first three parts. The objectives of the five parts are described below:

1. Assessment of future trends in industrial hydrogen demand and transport

Projecting demand of hydrogen in industries (as well as other sectors) and understanding the current and projected available infrastructure to accommodate these needs. Here, we will need an understanding of not only how much hydrogen will be in demand, but also the implications of competing energy carriers in meeting that demand.

2. Hydrogen cost implications

Understanding the costs of the full value chain for hydrogen energy carrier production, transportation, storage, and conversion, both inside and outside of the Netherlands, and in the form of different energy carriers.

3. The technological value chain for hydrogen

Gaining a comprehensive overview of the maturity/scale/learning curves/etc. of available technologies for production of hydrogen, transportation, storage, and conversion of different hydrogen-containing energy carriers, as well as an idea of how the technologies will continue to develop over the coming years and where promising technologies require further scaling up.

4. Dutch systemic scenarios for the hydrogen supply chain

Based on the demands, costs, and available technologies, anticipating which scenarios for energy carrier adoption are likely to play out in the coming decades and understanding what the systemic implications of these scenarios are for Dutch infrastructure and industry, both in terms of costs and impacts.

5. Public engagement for the hydrogen supply chain:

Communicating about the barriers to and implications of the transitions that will need to take place. The aims of communication include increasing public understanding and acceptance of the transitions happening in Dutch industries, ensuring Dutch industries and infrastructure have the right type of support from policy, and informing other industries' decision-makers about developments taking place in this area.

This project covered part 1 of the 5 parts described above.

1.3.2 Research Question

The main research question of this project is: **What are the major tipping points influencing the shift; from incremental change towards rapid growth in hydrogen economy, across various sectors?**

The goal of the project is to explore: demand in the Netherlands for industry, built environment and mobility sectors. Primary focus is on the industry sector of the Netherlands. In addition, the project provides insights on following aspects:

1. Literature review

a. Projected range in hydrogen use based on recent studies
b. Constraints, factors, and tipping points which appear to have the highest impact on hydrogen supply, demand, and infrastructure

2. Hydrogen demand

a. Possible hydrogen demand in 2050 for various sectors
b. Findings from interviews and literature studies
c. Identification of major tipping points which drive a low H2 demand scenario towards a high H2 demand scenario
d. Sensitivity analysis based on tipping points, using IN2050[1]

3. System effects and boundaries

a. Identification and localization of cluster effects
b. Consequences on existing infrastructure

1.4 Reading guide

The following chapter 2, provides an explanation of the project approach including overview of tools and interviews conducted. In chapter 3, findings from meta-analysis of 18 recent studies have been depicted. The chapter provides an overview of projected range for hydrogen use, based on these studies.

Thereafter, chapter 4 details out possible trends in different sectors for hydrogen demand. The results of the interviews and enabling factors for implementation (tipping points) of hydrogen with its potential demand for each sector have been described. Chapter 5 details out the findings of

[1] https://www.royalhaskoningdhv.com/en-gb/news-room/news/moving-beyond-predictions-in-the-energy-transition/7735

IN2050 to forecast demand of hydrogen as a fuel for industrial heating systems. The demand in 3 scenarios: base, low and high, are estimated through quantification of most important tipping points identified from chapter 4.

Chapter 6 describes the tipping points, which are majorly responsible for differences in demand of hydrogen for low and high case scenarios. Later, chapter 7 provides deep insights into system effects and boundaries arising from the tipping points. Finally, chapter 8 outlines key conclusions and recommendations following this study with recommendations on future steps for HyChain.

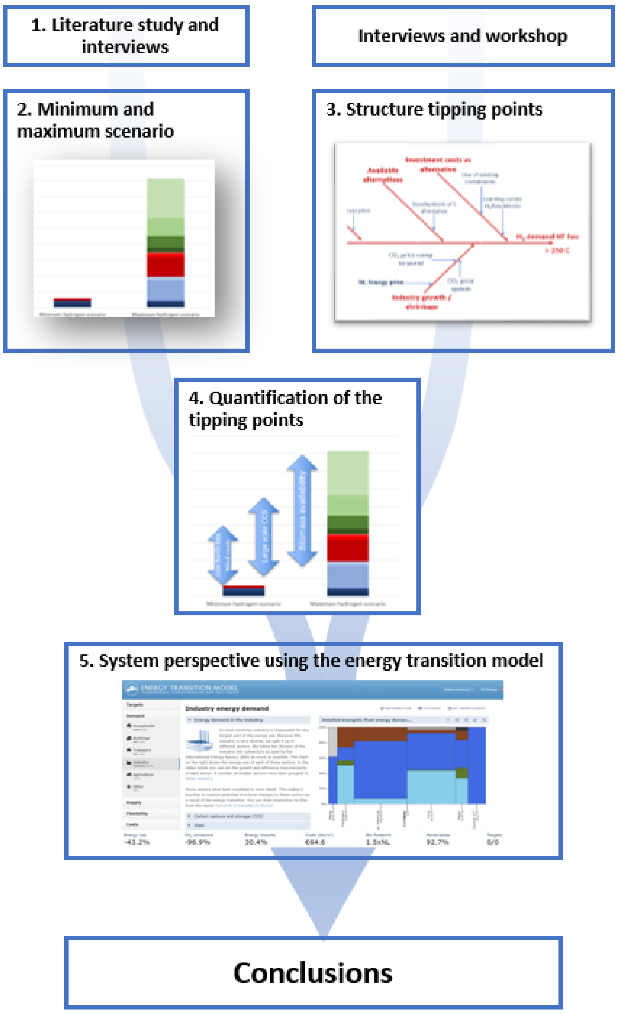
2. Approach

The objective of this study is to identify, the possible hydrogen demand in 2050 with an industrial focus. Many studies on hydrogen have already been performed but most of them do not provide in-depth insights into consequences for each sector within industries. On the other hand, a lot of industries have identified possible decarbonisation routes for their own processes. This information was collected through literature review and interviews of industrial partners.

Early in the process, we noticed a large bandwidth for hydrogen demand in the literature. Also, in the interviews a lot of alternatives to hydrogen were identified. Many scenarios to deal with this were already presented in various literature. In this study, we provided insights into the possible hydrogen demand by identifying the most important tipping points catalysing the demand growth.

In order to identify the tipping points and analyse the hydrogen demand which they influence, we performed the following steps:

1. Literature study and interviews to identify all hydrogen uses and their alternatives
2. Create boundary scenarios: low and high demands, based on the alternatives.
    a. For the low scenario, if possible a non-hydrogen alternative is chosen.
    b. For the high scenario, all the alternatives with hydrogen are chosen.
3. Using the interviews and a workshop with project partners, the major tipping points were identified. These were structured using a fish-bone approach to identify interconnections and missing aspects. These tipping points helped explaining why a high or low hydrogen demand is more likely.
4. The next step was quantification of the tipping points. This was performed to validate the consequences of a tipping point (using IN2050 for industry heat). The quantification was based on the information about possible hydrogen demands and the possible alternatives. The reasoning resulting in this quantification was probably more important than the number itself.
5. Using the ETM, dependencies and boundaries from a system perspective were identified.
6. Finally, most relevant conclusions were formulated, and recommendations were identified.



3. Literature overview

To acquire a general overview of future supply and demand of hydrogen in the Netherlands, we have performed a meta-analysis of 18 recent studies (see: Annex B). The scope of these studies varies significantly. In first section (3.1), we have described a few of these differences in dimensions, such as time horizon, type of scenario, geographic scope, type of model, variety in sectors and applications, and comment on the methodology we followed to allow a fair comparison. In section 3.2, we have described the existing role of hydrogen in the Netherlands in terms of supply, infrastructure, and demand. How the role of hydrogen for these three categories may evolve, according to the studies, in the future is explained in the next three sections. We have concluded this chapter by providing the key observations acquired from the literature review.

3.1 Comparing the studies

To acquire a general overview of the future demand of hydrogen in the Netherlands we have performed a meta-analysis of 18 recent studies (see: Annex B). The scope of these studies varies significantly. In this chapter, we have described a few of these differences in dimensions, such as time horizon, type of scenario, geographic scope, type of model, variety in sectors and applications, and comment on the methodology we have followed to allow an adequate comparison.

Time horizon and emission reduction target

The type of scenario is often determined by a set of ultimate goals, which should be fulfilled by the model or vision. Reduction in GHG emissions is probably, the most dominating criterion and, for most studies was set to 95% and often such a target should be realized in 2050. Some studies aimed for lower emission reductions: for instance, 49% if the time horizon goes not beyond 2030; or 80% in 2050 for less stringent scenarios. We mainly compared the reported numbers for 2050 with each other and if a study contains multiple scenarios we at least selected the one with the highest hydrogen use and/or with the highest emissions reduction target.

Region and country

It is highly unlikely that hydrogen will become a substantial energy carrier only in the Netherlands. Therefore, we also included, the projections of studies of other regions and countries, such as global outlooks, European analyses, and case studies for other countries than the Netherlands. To compare these projections for a specific year with the studies for the Netherlands, the numbers were corrected by the relative size of the Netherlands in terms of gross domestic product (GDP) which is projected for that specific year (OECD, 2019; Shell Sky, 2018). For instance, if the GDP of a country or region is about ten times bigger than of the Netherlands, the numbers on hydrogen use of that country or region was divided by a factor ten. In section 0 the results from the different regions were compared with each other.

Model or vision

Hydrogen supply and demand projections were either performed using a detailed model or were rough estimates based on a vision or roadmap. The modelled approaches can for instance provide an (cost-) optimized system, subjected to a set of boundary conditions, or a simulated system based on an estimated supply-demand goal. The level of details and the results vary among the models, as they strongly depend on the assumptions made in their input parameters (e.g. economic growth, available technology options, their costs, etc.). Visions and roadmaps are typically underpinned storylines on how a system may evolve, though often lack economic analysis and comparison with alternative options and thus, possess a higher order of uncertainty. We have shown results ranging from integrated assessment models to visions next to each other and discussed the differences between models and visions in section 3.5.1.

Sectors and applications

Hydrogen demand in a specific sector is often dominated by one or two applications of hydrogen use which is listed in section 3.2. Some studies categorized hydrogen use per sector, while others classified per application. We have considered the listed applications in section 3.2 as interchangeable with hydrogen use in a sector and often only referred to the latter. We shortly commented on our approach in the next paragraph.

In the built environment, mainly low temperature heat is required, while high temperature heat is needed in industry. Industry is also the major demand sector for non-energy use of hydrogen. Hydrogen as fuel for mobility is covered by the transport sector and as fuel for power generation (including its use as demand response option and for energy storage) is subscribed to the power sector. We should note that this approach is to some extent causing deviations, e.g. heat use in industry is considered as high temperature heat only. Within the uncertainty range of the projections, these deviations in the projected hydrogen demand by certain applications or sector are relatively small.

Not all studies included all sectors, e.g. the analysis by Dechema only covered industry (Dechema, 2017). In some studies, specific applications of hydrogen use were excluded. In the Sky scenario (Shell, 2018), for example, only energetic use of hydrogen was included, and the authors deliberately excluded the role of hydrogen for CO_2 conversion and as feedstock for industry. To determine the range in total hydrogen, use and to calculate the averages in the comparison of different types of studies (corrected for the relative size of national/regional GDP), we used the data from all studies without correction for lacking applications. Although this influences the average use of hydrogen, the projected range remains the same. Studies that do not explicitly mention hydrogen use for specific applications or sectors were not used to calculate the average hydrogen use for these applications or sectors in section 3.4.3.

3.2 Categories of application

Hydrogen is a versatile energy carrier and can be applied in various ways. We identified five major categories for application of hydrogen as listed below. How we differentiate between hydrogen use for energy and non-energy purposes is defined in Annex B. In a few recent studies a similar list of applications was reported, and the systemic role of hydrogen and other power-to-X energy carriers is described in more detail (FCH2JU, 2019; Frontier, 2018).

- Low temperature heat (buildings)

  Hydrogen can be used in gas networks (either directly as pure hydrogen gas or mixed with natural gas or bio-methane) to supply energy for space heating and in principle also for cooking in buildings.

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- Fuel for electricity generation (power)

  To cope with the intermittency of renewable power generation, a certain share of power generation should be dispatchable to provide the required flexibility. During periods with less sun and wind, gas turbines or stationary fuel cell systems, both running on hydrogen, can respond fast to provide electricity and stabilize the grid. Hydrogen may also play a role in that renewable electricity can be converted into hydrogen to circumvent grid congesting.

- Fuel for transportation (transport)

  In the transport sector battery electric vehicles are expected to take over a high share of road transport. Heavy duty transport, shipping and aviation are however more difficult to electrify, and other renewable fuels seem required. Hydrogen-driven fuel cell electric vehicles (FCEVs) may provide a solution for some of these applications such as buses, trucks and specialty vehicles. In addition, hydrogen can also be used for the conversion of biomass or CO_2 (or N_2) into biofuels and renewable synthetic fuels for transport applications such as planes and ships.

- High temperature heat (industry)

  Some industrial processes require high temperature heat. Currently this heat is mainly provided by the combustion of natural gas, which is delivered via the gas network. Similar as for low temperature heat, biomethane or hydrogen can be blended into the natural gas network for decarbonization. Alternatively, an increasing share of the network can be turned over to pure hydrogen.

- Non-energy use of hydrogen (industry)

  Industry consumes fossil resources also to produce various products. Most of these products eventually are incinerated, decomposed, or combusted with release of CO_2. Hydrogen is a versatile energy carrier and can be used as feedstock for the production of fertilizers, iron and steel, chemicals, and plastics. Industrial production of synthetic transportation fuels, as mentioned above (transport), will also increase hydrogen demand of industry, although in some studies this share of hydrogen use is ascribed to the transport sector.

These five categories of application are ascribed to four different sectors as depicted above (between parentheses). Detailed knowledge about each of these sectors is required to obtain well-informed estimates of their future size and properties and the potential hydrogen demand in each of them. Also, the cross-sectorial relationships and available alternatives are important to address. Overall these insights will lead to a more precise analysis of the role hydrogen can play in the entire energy system.

3.3 Hydrogen supply in the future

Steam reforming of fossil fuels, mainly natural gas, currently provides nearly all hydrogen for industrial use. In this process carbon is converted into CO_2 and is mainly emitted. In the ammonia industry a part of the CO_2 is captured for use in follow-up processes, in particular urea synthesis. Hydrogen produced from fossil fuels, accompanied by CO_2 emissions, is also referred to as ***grey hydrogen***.

For future hydrogen supply, the role of routes to produce hydrogen from fossil fuels while capturing and storing the CO_2 emissions are also explored. This so-called ***blue hydrogen*** often originates from the decarbonization of natural gas by ATR/SMR with CCS. Conventional production plants are equipped with carbon capture technology, which can avoid up to approximately 90% of the CO_2 emissions. The captured CO_2 is compressed and exported to permanent underground sequestration sites, for instance under the North Sea.

Production without CO_2 emissions from fossil energy provides ***green hydrogen***. Water electrolysis driven by renewable electricity is the prime example of such a process. The renewable electricity potential can be directly related to the green hydrogen production potential if import of renewable electricity and green hydrogen are not taken into account. Alternative green hydrogen production routes also exist, for instance via gasification of biomass. For this route the availability (and costs) of biomass is of prime importance for the hydrogen production costs. In a process with biomass as feedstock, the combination with CCS even leads to the production of hydrogen with negative emissions.

In 2050, the high CO_2 emission reduction targets probably only allow supply of zero-emission hydrogen. In the studies the ratio between blue and green hydrogen supply varied from fully blue to entirely based on green hydrogen. Multiple factors, such as the relative costs of blue and green hydrogen (either domestically produced or imported), the potential for CCS, the ambition of the emissions reduction target, the availability of enough renewable electricity, and the performance of the required conversion technology, determine the resulting hydrogen supply chain. On the long-term green hydrogen production is the most sustainable solution, but in the short to medium term – i.e. during the initial growth phases of hydrogen as an energy vector – a role for blue hydrogen seems likely. The projected output shares of different hydrogen production routes probably rely in particular on their relative competitiveness, as affected by the factors mentioned above (see also CE Delft, 2018 and FCH2JU, 2019).

Future supply of hydrogen in the Netherlands can consist of domestic production, based on domestic (renewable, low-carbon) energy sources – including sources from the Dutch part of the North Sea – and/or imports from other countries, both inside and outside the EU. The ratio between domestic production and foreign imports of hydrogen depends primarily on the relative costs of these two options, including the costs of transport, etc. To some extent, however, this ratio may depend also on political considerations, i.e. the extent to which the Netherlands – or the EU as a whole – is willing to depend on foreign resources for its energy security.

3.4 Future hydrogen infrastructure

Currently, hydrogen is primarily produced and consumed by industry, while some facilities for transport and distribution of hydrogen exist across the industries involved (see also section 1.2). Increase of future supply and demand of hydrogen will depend on a dedicated national transport and storage infrastructure with cross-border connections. If sufficient renewable electricity is available, green hydrogen shall probably be produced in or close to areas where renewable energy is harvested, e.g. near offshore wind parks, in order to limit investments in relatively expensive electricity distribution infrastructure as much as possible. These production sites have to be connected via pipelines to the existing infrastructure. An alternative onshore option for mobility is to transport hydrogen via trucks, either after liquefaction or compression, to for instance filling stations for the transport sector.

In the Netherlands an extensive, cross-border infrastructure is available for natural gas. Hydrogen can (due to legal and technical reasons) only to certain limit be injected in the natural gas grid. It is possible to convert natural gas pipelines into hydrogen pipelines (DNV GL 2017). Gasunie has calculated that a section of the current high-pressure gas grid can be dedicated to creating a so-called national hydrogen backbone (Gasunie, 2019). Conversion of (segments of) the existing natural gas network into a hydrogen network will serve as an enabler for the development of the hydrogen option. These existing gas grids can connect the different industrial clusters rather easily and facilitate the roll-out of hydrogen throughout the other end-use sectors.

In the existing gas network buffering for peak demand is solved by storage of natural gas in underground gas fields and salt caverns. Storage of hydrogen in salt caverns is already a proven technology. Due to the lower energy density of hydrogen the energy storage capacity (both in the gas grid and underground) is only one third of that of natural gas. Storage in old gas fields is less developed and traces of natural gas might decrease the purity of the hydrogen.

The existing natural gas network can be used not only for the transport, distribution, storage, and transit of domestically produced hydrogen – including on the North Sea – but also for the import of renewable hydrogen. Import of renewable hydrogen is, however, also possible as ammonia, in which hydrogen is bonded to nitrogen, or as carbon products, such as liquefied synthetic natural gas, methanol, or hydrocarbons. For each of these energy carriers dedicated infrastructure already exists.

3.5 Hydrogen demand in the future

Most of the studies reported multiple scenarios of which only one or two are displayed in our analysis to limit the amount of data and to ease comparison. To acquire the broadest range possible, at least the scenario with the highest projected amount of hydrogen use was included. Figure 2 depicts how the projections in hydrogen demand vary over the different studies. At the starting point, (2015) the hydrogen demand ranged between 0 and 110 PJ/yr. This discrepancy is caused by the assumptions made in the studies. The low estimate is explained by the fact that some studies only analysed the (future) demand for energetic use of hydrogen, which is currently nearly zero in the Netherlands. In other studies, the current non-energetic use of hydrogen was included leading to the high value of 110 PJ/yr.

Although a few data points were found for 2030, most studies looked further ahead and modelled or envisioned the situation in 2050 (or in a zero-emission society). The projected hydrogen demand in 2050 covered a broad range, namely between 0 and almost 1900 PJ/yr (or from 0 to almost 16 Mt/yr)[2]. In the most conservative studies, the role of hydrogen was negligible in comparison to total energy consumption and no substantial market for green hydrogen developed before the half of this century. In these studies (e.g. DNV GL, 2018; IEA, 2017; Shell, 2018), the potential of hydrogen was recognized but its penetration before 2050 was still considered as limited. In, for example, the

[2] Conversion factor: 1 PJ H_2 = 0.00833 Mt H_2 (LHV H_2 = 120 MJ/kg)

Sky scenario (Shell, 2018), which gave a projection until 2100, hydrogen use started to develop from 2040 onwards and was deployed at scale only in the second half of the century.

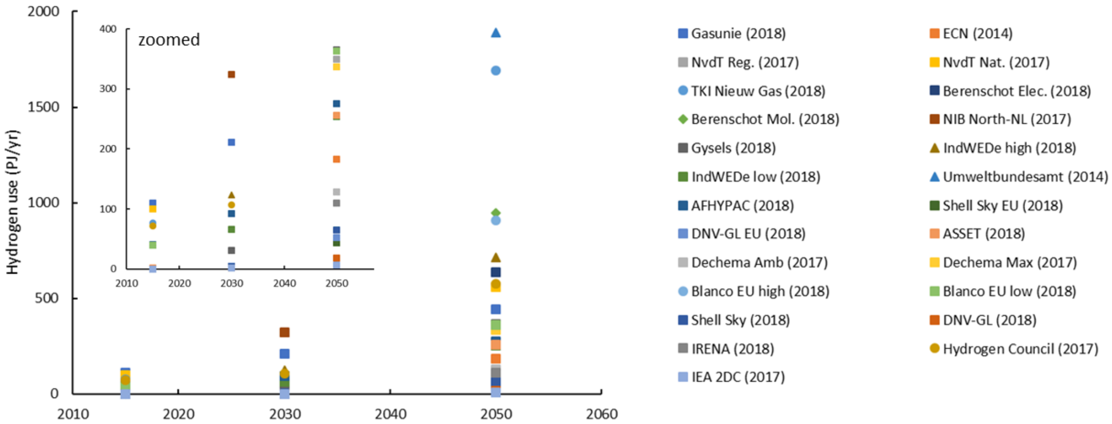

Figure 2: Total hydrogen use in the Netherlands (values for other countries or regions are GDP corrected)

Overall, we have observed an upward trend in the projected hydrogen demand. The broad range revealed that there still exist many uncertainties in the exact role hydrogen will play in the future.

Two studies stand out in their estimates of the potential demand for hydrogen: *Outlines of a Hydrogen Roadmap for the Netherlands* (TKI Nieuw Gas, 2018)[3] and *Germany in 2050 – a greenhouse gas-neutral country* (Umweltbundesamt, 2014). In both studies, a significant amount of hydrogen is required to convert CO_2 into carbon-based products, such as methane, kerosene and diesel, and feedstocks for chemical products and materials. These two studies strongly influenced the averages in our analysis, but they seem very relevant if one wants to understand which assumptions lead to a high potential of future hydrogen use.

[3] The TKI Nieuw Gas study gives only an outline on how the use of hydrogen may evolve in the future. The final year is not mentioned, but we have positioned it at 2050 to allow comparison with most of the other studies.

Regional and country effects

Figure 3, presents the use of hydrogen per sector (and in total) in 2050 as projected in the reviewed studies covering either (i) the Netherlands, (ii) other individual EU countries (notably Germany, France or Belgium), (iii) the EU as a whole, and (iv) the world as a whole (where the projected numbers for other countries or regions besides the Netherlands have been corrected for the relative size of their GDP). In addition, Figure 3 also shows the average hydrogen use over the studies covering each of these four geographical categories (indicted by the vertical dash line in Figure 2). We note that the average use throughout our analysis is probably relatively high because we have, if multiple scenarios are reported in the consulted studies, mainly selected the high hydrogen demand scenarios (as mentioned above).

From Figure 3, it becomes clear that the average (GDP corrected) total hydrogen use in 2050 across the studies covering either the Netherlands or other individual EU countries (Germany, France or Belgium) is more or less similar (i.e. almost 700 PJ/yr), while it is substantially lower for either the EU or the world as a whole (i.e. almost 300 and 160 PJ/yr), respectively). Based on the available information provided in the studies considered, these differences in projected average hydrogen use are hard to explain specifically but are most likely related to the basic characteristics and the related, underlying modelling assumptions regarding the countries and regions concerned (notably on the availabilities and costs of hydrogen and other, competing energy sources).

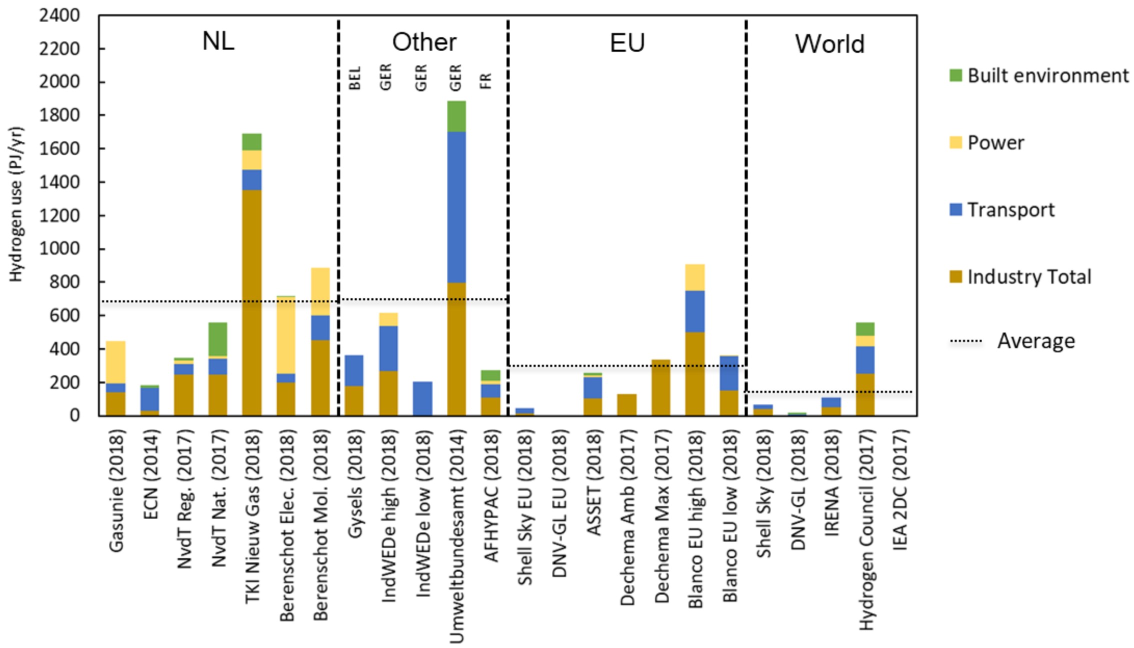

Figure 3: Hydrogen use per sector in 2050 (values for other countries or regions besides the Netherlands have been corrected for their relative GDP size)

The four colors in the bars in, Figure 3, indicate the four end-use sectors in which hydrogen is used. Although some studies covered only one specific sector (e.g. industry in the Dechema study), most studies took all sectors into consideration. In several bars one or more colors are lacking, which apparently indicates that in these sectors hydrogen use is not expected to occur under the assumptions of the scenario. In sector 3.5.2 we have tried to address in more detail why these sectorial differences are observed.

3.5.1 Model or vision

Categorization of the results according to the type of study, being either modelled or visualized, indicates that a clear difference in average use of hydrogen exists between models and visions, in which the latter shows a higher average use (resp. 331 and 692 PJ/yr, Figure 4). The higher average for the visions is mainly caused by the two highest estimates (Umweltbundesamt and TKI Nieuw Gas) that belong to this category. Interestingly, the next two highest estimates (Blanco EU high and Berenschot Molecules) were both modelled scenarios, either using an optimization model or a simulation model, and project a higher hydrogen use than the seven other visions. This indicates that the results are mainly determined by the assumptions made by the scenarists/modelers and the input parameters used in the models. The differences in assumptions can already be seen by the distribution of hydrogen use over the sectors (indicated by the different colors). The variation per sector and the underlying assumptions have been discussed in more detail in the next section.

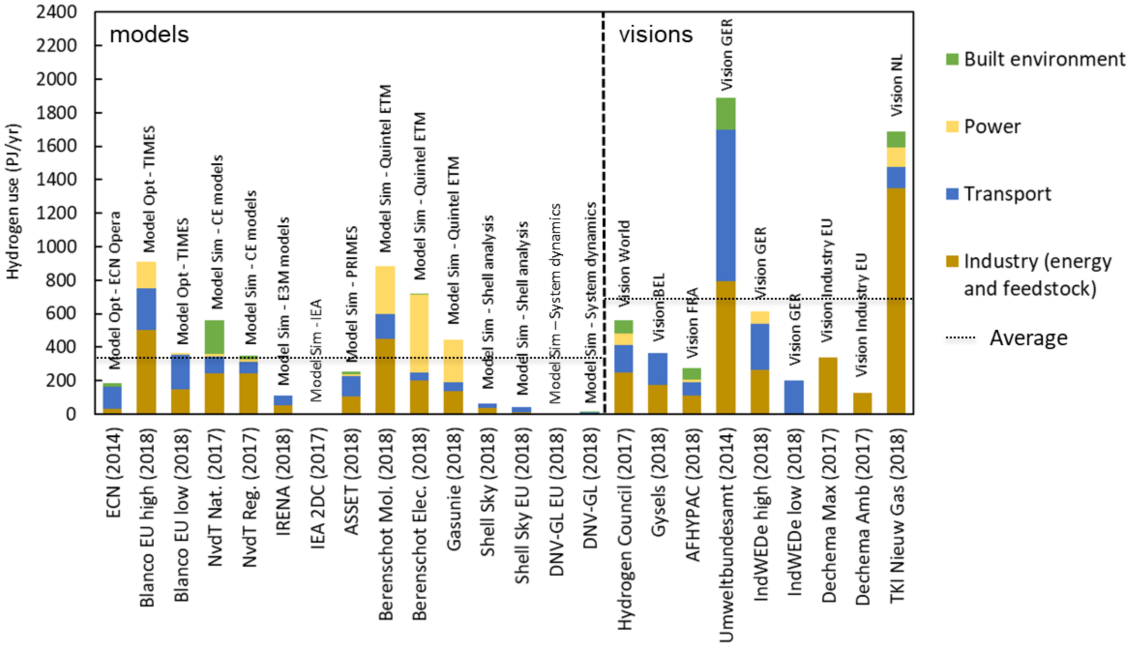

Figure 4: Hydrogen use per sector in 2050, categorized per type of study

3.5.2 Sectors and applications

The estimates for hydrogen use in the future varied widely among studies and sectors. In this section, we have described some of the underlying assumptions that cause the existing ranges for each end-use sector. We have showed, the results from the studies by plotting two ranges of hydrogen use in 2050: low (dark-colored area) and high (light-colored area) in comparison to the average of all studies for which a value is reported for the sector concerned (see example in Figure 5). The low range starts in each case at zero and extends until the average, while the high range starts at the average and stretches until the maximum value from all studies. Alongside of the high range bar, we have noted the main assumptions to reach these high projections of hydrogen use.

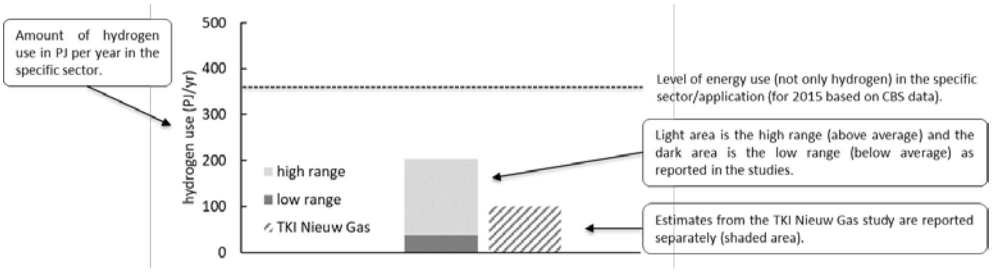

Figure 5: Example of how we illustrate the results for each sector

Next to the low and high ranges, the results from the TKI Nieuw Gas study have been depicted separately because these estimates are based on clear assumptions and help to understand to what extent these assumptions affect the level of hydrogen use for a specific application or sector. The dashed line in the figures, which indicates the 2015 level of energy use in the sector concerned, also assists in putting the amount of hydrogen use into perspective of current energy demand by a specific application or sector.

Buildings

In the built environment, our main energy source for heating today is natural gas. Energy savings are expected by increased insulation and electrification, resulting in a lower energy use in this sector by 2050. Electric heat pumps and boilers, geothermal systems and industrial waste heat via heat networks are expected to provide the majority of heat for buildings. However, for some locations these solutions are not enough; either practically not feasible or more expensive than using the existing gas network. For these cases, renewable gas in the form of biogas, synthetic methane or hydrogen can replace natural gas and provide a sustainable alternative. The share of renewable gas and the portion of hydrogen in it depends on the relative costs and availability of the alternatives. In some studies, a zero demand for hydrogen was expected, while in others half of energy demand (approximately 200 PJ/yr) for heating buildings was provided by hydrogen gas (Figure 6). The average projected hydrogen use was only 34 PJ/yr, mainly because in roughly half of the studies hydrogen was not used to generate low temperature heat.

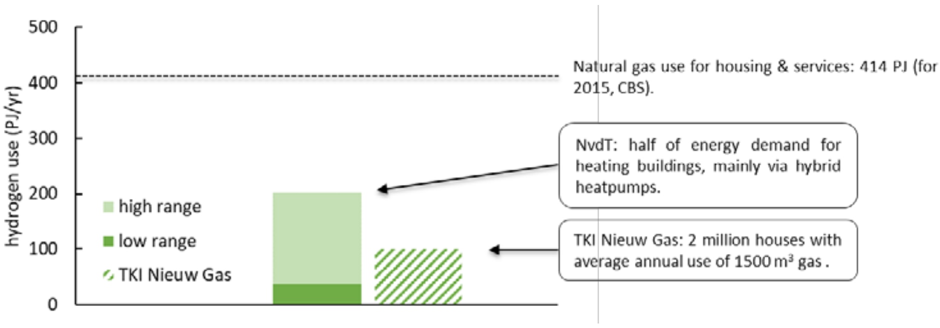

Figure 6: Hydrogen use in 2050 in the built environment

Power

Currently, our electricity production mainly relies on powerplants running on fossil fuels. The closure of coal and nuclear powerplants and a steady increase of renewable power supply from solar and wind drastically changes the electricity system. Flexibility options that can stabilize electricity supply include flexible (dispatchable) power generation, demand response, energy storage and (cross-border) power trade.

It is expected that a specific share of power production should remain dispatchable to function as back-up for intermittent renewable energy supply. These dispatchable power plants should be able to respond fast when necessary. In the concept climate agreement for the Netherlands, is stated that to ensure the security of supply enough dispatchable power is essential, which should become increasingly free of CO_2 emissions (SER, 2018). In 2030, 17 TWh of dispatchable production may already be required, although probably not fuelled by hydrogen. While many studies did not expect any hydrogen use for future power supply, some studies did foresee a substantial role for dispatchable, hydrogen fuelled powerplants, CHP plants, or fuel cells (Figure 6). Often these solutions come up if both (intermittent) renewable electricity supply and emission reduction targets are high.

As for all applications, either blue hydrogen, as a decarbonized form of natural gas (if CCS is accepted), or green hydrogen can be used for power production. From an efficiency point of view, however, the route to generate electricity via green hydrogen, if obtained by water electrolysis, seems not straightforward because the renewable electricity, which is required to produce the hydrogen, can also be used directly. This less efficient route may, however, become attractive if the system is put under severe constraints (e.g. no/low CCS and high emission reduction targets) or if different sectors can mutually benefit from e.g. shared energy storage facilities.

In the left plot in Figure 7, the projected hydrogen-fuelled electricity production is depicted in TWh/yr to enable comparison with current electricity use.[4] The total amount of hydrogen expressed in PJ/yr (right side of Figure 7) is relatively higher because of estimated efficiency losses of 35–60% in the conversion processes to produce electricity.

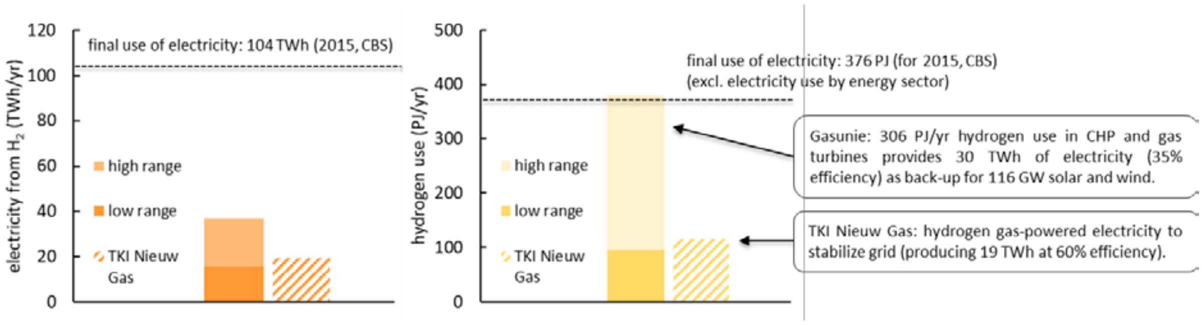

Figure 7: Hydrogen use in 2050 for electricity production

Transport

Currently, hydrocarbon fuels, derived from fossil oil, are the main energy source for transport. Energy use in the domestic transport sector in the Netherlands accounts for more than 400 PJ/yr, while bunker fuels for international aviation and shipping represent almost 700 PJ/yr (or 5.8 Mt/yr). The emissions of the latter category are not part of the national CO_2 emissions bookkeeping and are thus, usually not considered in national studies and scenarios.

[4] Although almost all energy is depicted in PJ (e.g. hydrogen), electricity we express in the more commonly used TWh as far as possible (conversion factor 1 TWh = 3.6 PJ).

In European and global studies, energy use for international aviation was included in the energy demand figures, while marine bunker fuels are only included in the energy demand accounts of the transport sector in global analyses. This bunker fuel demand may, thus, cause slight variations in the projections for hydrogen use. However, in our analysis we did not observe a clear relation between an increased energy demand by aviation and shipping (in the European and global assessments) and hydrogen use.

Only considering road transport, many studies projected a rapid shift to BEV for cars and other light duty vehicles. Heavy duty vehicles, such as trucks, are more difficult to electrify. In this category the assumptions differ, and hydrogen sometimes plays a significant role as fuel in FCEVs. Alternative options for hydrogen are, besides batteries, bio-, fossil, and synthetic hydrocarbon fuels. The respective performances (e.g. in terms of costs, emissions, noise, pollution, and driving range) will determine the relative share of each of these options. The same alternatives exist for aviation and shipping but with other requirements for the fuel. As a fuel with a high energy density is preferable in these categories of transport, renewable hydrocarbon fuels seem most promising but direct use of hydrogen may be an option too.

Correcting study results for the relative GDP size of the countries or regions considered, showed that, almost each study projected in 2050 at least 10 PJ/yr of hydrogen use in the transport sector. The average use was 160 PJ/yr, while the highest estimate reported more than 900 PJ/yr mainly for synthetic fuel production (Figure 8). Under the assumption that all diesel engines are replaced by hydrogen-driven FCEVs, hydrogen use by road transport is around 125 PJ/yr (TKI Nieuw Gas, 2018). If diesel is replaced by synthetic hydrocarbon fuels produced from CO_2 and H_2, hydrogen demand increases further due to efficiency losses in the conversion process. Synthetic hydrocarbon fuels for aviation and shipping are more likely to become reality and have a substantial impact on hydrogen use (>700 PJ/yr) if they have to replace all current bunker fuels in the Netherlands. Some studies counted the hydrogen use for these processes to the transport sector (e.g. Umweltbundesamt, 2014), while others appointed this to industry (e.g. TKI Nieuw Gas, 2018).

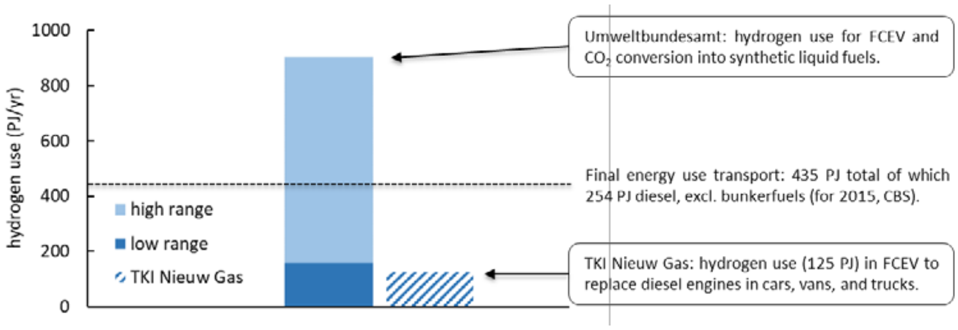

Figure 8: Hydrogen use in 2050 in the transport sector

Industry

In 2015, most energy is consumed in the industrial sector (energetic use 554 PJ/yr), especially in combination with non-energetic use of fossil fuels as feedstock (non-energetic use 504 PJ/yr, see Figure 9). In a recent perspective from the World Energy Council Netherlands a case was presented in which hydrogen-based technologies in industry acted as catalyst for the deployment of a hydrogen economy (WEC NL, 2019). Industrial processes often require high temperature heat, which is generally generated by the combustion of natural gas. Ninety percent of the reported studies projects a role for hydrogen to provide high temperature heat for industry in 2050. Although electricity-driven heating systems seem promising to generate low temperature heat in buildings, alternatives that can produce high temperature heat of more than 250 °C are less advanced. Replacing natural gas by hydrogen is expected to become attractive to decarbonize high temperature heat demand in industry. If current heat demand stabilizes, approximately 100 PJ/yr of hydrogen is required to replace this share of natural gas. More hydrogen (up to 288 PJ/yr) is required if hydrogen is first converted in synthetic methane by reaction with CO_2, as described in a study for Germany (Umweltbundesambt, 2014). This route suffers, however, from additional investments in conversion equipment and efficiency losses. We should note that the Dutch situation allows for the construction of a dedicated hydrogen infrastructure fairly easily, which renders prior conversion to methane unnecessary. The relative performance of the many alternatives to provide high temperature heat, such as electric heating, solar and geothermal technology, and biomass and waste to heat options, will eventually determine the actual share of hydrogen use for heating. Currently, it is still a challenge for most alternative options to provide temperatures >500 °C in a practical manner. Therefore, it seems not surprising that in most studies a substantial role is projected for hydrogen use for heating purposes in industry.

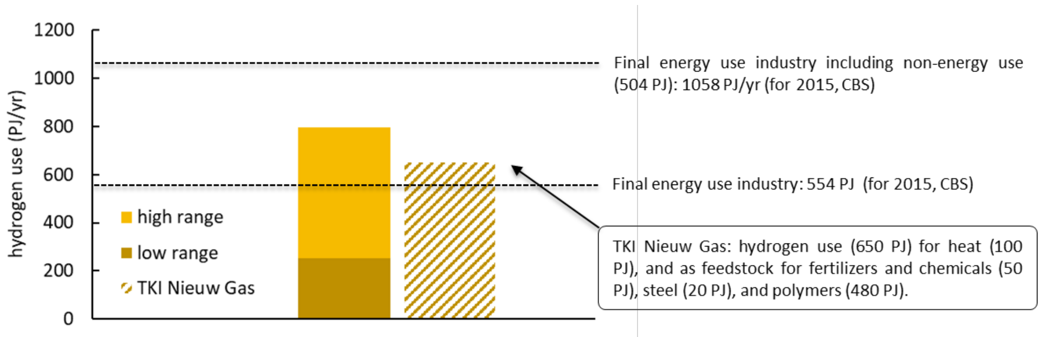

Figure 9: Hydrogen use in 2050 in the industry

The projections increase substantially if hydrogen is also used as feedstock in industry. Hydrogen, produced from natural gas, is already used today at a scale of approximately 110 PJ/yr as feedstock in chemical processes, for instance to produce ammonia. Also, most common base chemicals, which are required to manufacture chemicals and polymers, have a fossil origin. Nowadays naphtha and gas condensates are the main carbon-based feedstocks for the petrochemical industry. Technology to convert CO_2 and hydrogen to synthesize base chemicals is already available, e.g. methanol synthesis and the methanol to olefins process, and Fischer-Tropsch (FT) synthesis of hydrocarbons. Implementation of such technology can reduce the consumption of fossil resources to produce carbon-based products. Production of most common base chemicals by utilization of CO_2, preferably captured from air, and H_2, increases hydrogen demand to at least 480 PJ/yr, which is the current amount of non-energy use of oil products (TKI Nieuw Gas, 2018).

Hydrogen may also be used as reductant in metallurgy, e.g. for steel production, and refinery processes. The latter category might diminish if hydrocarbon fuel use decreases. This, however, may not become reality if approaches to produce synthetic hydrocarbons are deployed to provide our need for renewable carbon-based transport fuel (see also section 4.4.3. Transport) and base chemicals. In such scenario, refining of the crude products from CO_2 conversion processes (e.g. from

FT synthesis) remains necessary. Industry based on the utilization of pure CO_2 will result in the highest hydrogen demand. Next to CO_2 from industrial point sources or air, carbon feedstocks can also be derived from biomass or plastic waste. These carbon materials already contain energy and would require less additional hydrogen for their conversion. The relative availability of carbon resources thus determines the demand for hydrogen to produce our renewable base chemicals, polymers, and fuels of the future.

3.6 Key observations from the literature study

Although a more extensive overview of conclusions and recommendations is provided in chapter 8, we have already shortly listed a few of the key observations from the literature study:

- Our analysis displayed a diverse role of projected hydrogen use in the Netherlands in 2050, ranging among the studies, from nearly zero to almost 1900 PJ/yr (16 Mt/yr).
- Hydrogen demand is specifically projected for the following applications:
    - as fuel for dispatchable power generation (up to 380 PJ/yr or 3.2 Mt/yr)
    - as fuel for transport (up to 905 PJ/yr (or 7.5 Mt/yr) if hydrogen use for synthetic fuel production for all modes of transport is included)
    - as fuel for high temperature heat in industry (up to 288 PJ/yr or 2.4 Mt/yr)
    - as feedstock for carbon-based products (up to 550 PJ/yr or 4.6 Mt/yr)
- Hydrogen use is highest when approaches; to produce synthetic fuels and feedstocks from CO_2, emerge.
- The complexity of the future role of hydrogen in an integrated system makes the use of optimization and simulation models desirable to obtain more detailed insight into the different relations and dependences.

4. Quantification of hydrogen use

In this chapter, the possible hydrogen demand and alternatives have been estimated per sector in 2050. This has been done to identify a high and a low hydrogen demand, scenarios. It is used as a basis for quantifications of the tipping points in chapter 0. The hydrogen demand is calculated; based on existing final use of fuels and feedstocks. Further, the projection in demand incorporated current hydrogen demand.

4.1 Industry

To identify the demand of hydrogen, the use of fossil resources by industry was divided into fossil feedstock and heat use in the different industrial sectors as classified by the CBS[5].

4.1.1 Feedstock for fertilisers

Currently, the fertiliser industry is one of the few industries which already use hydrogen as feedstock. In the Netherlands, there are two fertiliser plants; in Geleen and Sluiskil. Together, they use 68 PJ of hydrogen per year to produce ammonia. This hydrogen is produced by steam methane reforming (SMR) from natural gas. A small part of the ammonia is used as industrial chemical, the majority is converted further into fertiliser.

Nitrate based or urea

The final product is either nitrate-based or urea. The major difference lies at the point of supply chain, when the CO_2 is emitted. During the production of nitrate-based fertiliser CO_2 is emitted directly at the production site. For urea, on the other hand, the CO_2 is emitted during the use-phase (consumer side) as the urea molecule includes a carbon molecule. In a carbon neutral future, it is easier to use nitrate-based fertiliser because it can be made directly from hydrogen and when using methane, the CO_2 is easily captured at the production site. If urea is needed anyways, one has to use a 'green' methane or carbon source to avoid additional CO_2 emissions.

Feedstock demand and alternatives

There are three options identified, for the decarbonisation of the fertiliser industry. We assume that only nitrate-based fertiliser will be used because this is easier to produce in a carbon neutral way.

> Interview insights:
> Fertiliser industry is a global market, producing in Europe is relatively expensive because of the current gas price. This does open possibilities to switch to green fertilisers. This green market is currently very small, with only one costumer using it. An increase in green fertiliser demand will accelerate the change to green production. The key arguments of producing green fertiliser in the Netherlands are; access to energy from off shore wind and possibilities of CCS implementation.

[5] https://opendata.cbs.nl/statline/#/CBS/en/dataset/83140ENG/table?ts=1531929152076

1. **Use of methane and CCS (68 PJ hydrogen)** The production of hydrogen from methane is already in place. Also, the process CO_2 emissions are currently captured, and a small part is used in greenhouses and food industry. When adding storage this leads to a CO_2 neutral alternative, this would mean blue hydrogen is used as feedstock for producing fertilisers. With current SMR processes, it is difficult to capture all the CO_2. An alternative process using an auto thermal reformer (ATR) produces clean CO_2 which can be stored directly.

2. **Direct hydrogen use (68 PJ hydrogen)**
   For the fertiliser industry, importing the hydrogen is relatively simple to implement. Since, it is already an intermediate product in the process. This hydrogen can either be blue or green.

3. **Biomass as a source of methane (68 PJ hydrogen)**
   When biomass is used as the source of methane there is no need for CCS. The methane can be used in current SMR installations. In this case, only the source of methane changes. There are certain points for attention when using biomass for fertilizers. For example, when the same fertiliser is used to produce the biomass in the first place, an undesirable cycle is created. Using for instance, manure as a source does not cause this effect.

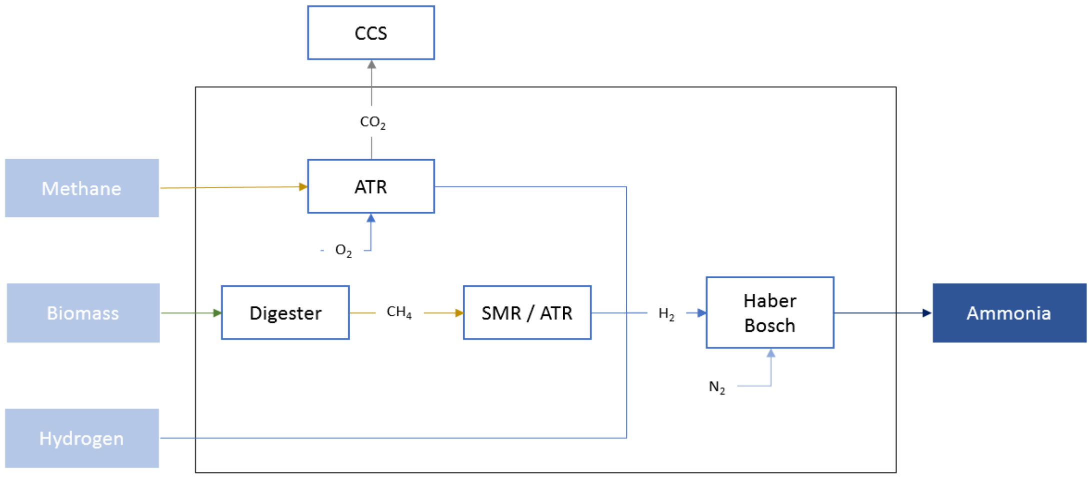

Figure 10: Identified chemical routes for ammonia production

Heat demand

Currently, 23 PJ of heat is used by the SMR units in the Netherlands for producing hydrogen from methane. When using hydrogen directly as a feedstock this heat is no longer needed (as SMR process is not required, see Figure 10). For the case in which, the SMR is still used it is likely that methane will fuel this process. In either way no hydrogen is used for heating purposes.

Low hydrogen scenario:

In all alternatives assuming that the industry stays in the Netherlands, hydrogen is used as feedstock. The production can be either local as it is right now or produced elsewhere. Therefore, the demand for low scenario is equal to the current hydrogen use.

High hydrogen scenario:

In the scenario we do not take growth or shrinkage of production into account, the demand for high scenario, is therefore, also the current hydrogen use.

4.1.2 Feedstock for methanol production

Feedstock demand and alternatives

The production of methanol requires hydrogen within the process. The main production site of methanol in the Netherlands is at BioMCN, with a yearly production of 900 kton methanol[6]. Using the following reaction; CO2 + $3H_2 \rightarrow CH_3OH + H_2O$; corresponds to a hydrogen consumption of about 170 kton or 20 PJ. The production of methanol does not emit CO_2 apart from thermal losses in the SMR. But a large amount of the produced methanol is used in energy conversion processes, thus, finally resulting in CO_2 emissions during the end-use phase. For the calculation of the maximum H_2 demand; we assume a CO_2 neutral world consequently, the methanol feedstock needs to carbon neutral as well.

The following CO_2 neutral alternatives are identified for this process:

1. **Hydrogen and CCU (20 PJ of hydrogen)**
   Methanol can be produced using green hydrogen and a "green" carbon source. This means that the carbon dioxide does not originate from a fossil source. The carbon source is for instance could be, CO_2 from direct air capture (DAC) or using biomass emissions from another process.
2. **Biomass as a source (0 PJ of hydrogen)**
   Biomass can provide both hydrogen and carbon, to produce methanol. One route is to digest the biomass into syngas, this can be used for methanol production. A shift reaction might be necessary to get the right ratio between hydrogen and carbon atoms.

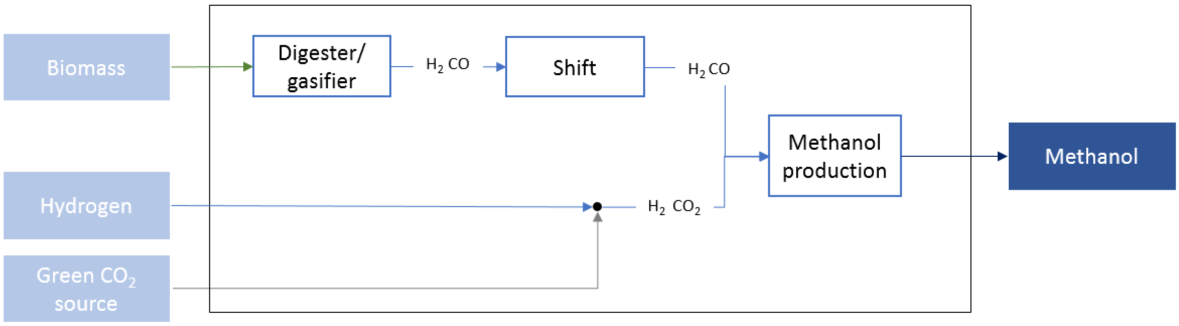

Figure 11: Identified chemical routes for methanol production

Heat demand

The methanol producing reactions are exothermic, so no additional heat is needed. As the heat demand is highly specific to process that will be adopted in future, the IN2050 modelling does not take this sector into account to estimate future energy mix of the industry sector in the Netherlands.

Low hydrogen scenario:
In the biomass case, there will be a need for 0 PJ of hydrogen.

High hydrogen scenario:
In the CCU case, there will be a need for 20 PJ of hydrogen. Because part of the methanol is used for fuels this might overlap with mobility, this is not corrected for.

[6] https://www.chemieparkdelfzijl.nl/actueel/2018/02/651479-biomcn-wordt-wereldspeler-in-methanolproductie

4.1.3 Feedstock and heat for petrochemistry

In the previous sections; the fertiliser and methanol sectors were covered. This section describes the rest of petrochemistry sector.

Feedstock demand and alternatives

In this large industrial sector, the primary feedstock use is concentrated at the steam crackers producing ethylene, propylene, C4 fractions, and aromatic compounds. In the Netherlands, at three locations, the total combined ethylene production capacity is 4045 kton per year[7]. The total amount of feedstock consumed is 7112 kton[8] a year with an energy equivalent of 420 PJ[9]. Moreover, 5609 kton ethylene of steam cracker capacity is located in the Antwerp-Rotterdam-Rhine-Ruhr Area (ARRRA)[10] and multiple pipelines exist to provide these with feedstock from Rotterdam refineries.

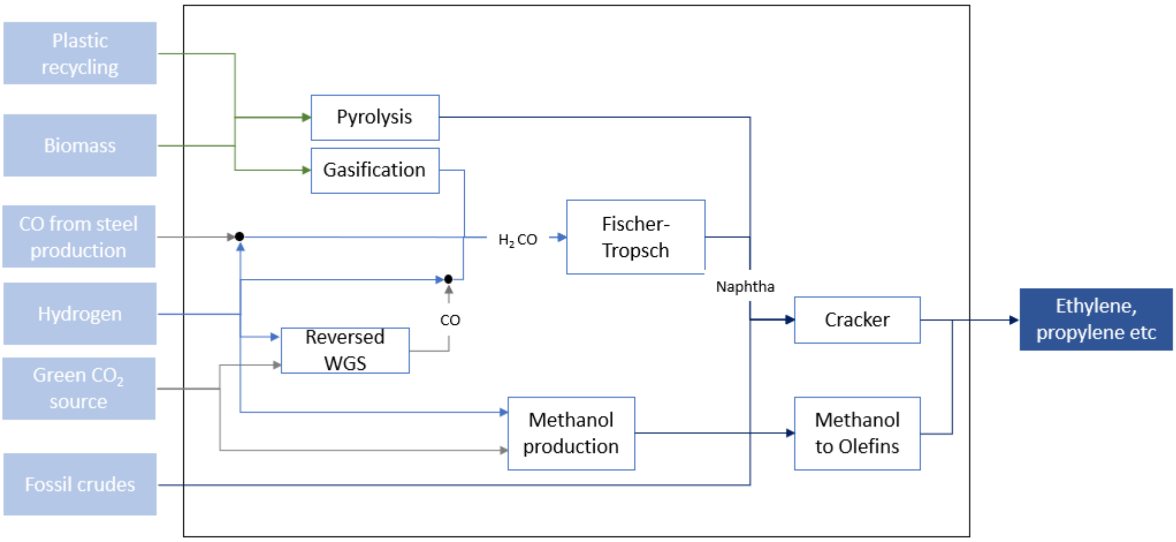

Figure 12: Identified chemical routes for hydrocarbon production

A dominant share of the products from the steam crackers is converted into plastic materials and fibres. The following options have been identified to possibly attain carbon neutral process:

1. **Bio based feedstock** to produce base chemicals. **(0 – 50 PJ hydrogen)**

   Second generation biomass can be used as feedstock for the petrochemistry using gasification and the Fischer-Tropsch (FT) process. For this route, the addition of extra hydrogen is an option to increase the hydrocarbon production from biomass. The reason for this is that a ratio of 2 between hydrogen and carbon in the synthesis gas is necessary for the FT process. This can be achieved by the water-gas shift reaction, in this case no extra hydrogen is needed. But in the case where biomass is scarce and using all carbons atoms from biomass is preferable, hydrogen must be added. In woody biomass H over C ratio is typically 1.4 (50%$_{weight}$ C, 6%$_{weight}$ H).[11] To reach the ration of 2, 0,02 kg of hydrogen must be added to every 1 kg of dry base

[7] https://www.petrochemistry.eu/about-petrochemistry/petrochemicals-facts-and-figures/cracker-capacity/
[8] https://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=83403NED&D1=a&D2=0-9&D3=71&HDR=G1,G2&STB=T&VW=T
[9] https://opendata.cbs.nl/statline/#/CBS/nl/dataset/83140NED/table?ts=1552597084163
[10] https://www.petrochemistry.eu/about-petrochemistry/petrochemicals-facts-and-figures/cracker-capacity/
[11] The Handbook of Biomass Combustion and Co-firing

biomass. This is only 2% in weight but in terms of energy, it is 12%. This is because the energy density per kilogram of hydrogen is a factor 6 higher relative to biomass. For the full Dutch demand, based on the current energy equivalent feedstock use of 420 PJ, this results in 50 PJ of hydrogen.

2. **CCU route in synergy with steel (43 PJ hydrogen)**
   A combination of steel and plastic production routes is a possible alternative, in which the carbon monoxide in the waste gas from steel production is used for plastic production. This carbon monoxide, together with hydrogen can be used as feedstocks for a Fischer-Tropsch (FT) process to produce hydrocarbons.

   Based on the results of the CORESYM study the production of one ton of steel can supply for 90 kg of hydrocarbons assuming a carbon efficiency of 51%[12]. With a Dutch steel production of 7 million ton a year this would lead to 630 kton of hydrocarbons which is roughly 9% of the total current 7112 kton[13] of feedstock for petrochemistry. The FT reaction uses 0,29 kg of hydrogen for every kg hydrocarbons. Therefore, the production of 630 kton hydrocarbons at a carbon efficiency of 51% corresponds to a need for ~360 kton of hydrogen.

   To conclude, this route can supply 9% of the total Dutch petrochemistry feedstock using 43 PJ energy equivalents of hydrogen.

3. **CO_2 utilization** capture and conversion of carbon dioxide from green emissions or air **(520 PJ hydrogen)**
   In this route CO_2 and hydrogen are used as feedstocks for a reversed water gas shift reaction and the Fischer-Tropsch (FT) reaction. To calculate the amount of hydrogen needed the following assumptions are used.
   a. Total petrochemical feedstock use in the Netherlands is 7112 kton[14] a year.
   b. Three H_2 molecules are needed for every CO_2 molecule[15], which corresponds with 0,43 kg hydrogen per kg hydrocarbons.
   c. A total carbon efficiency of the process 70%

   This results in a total hydrogen amount of 4.400 kton, which corresponds to an energy equivalent of 520 PJ

4. **Plastic recycling** trough gasification **(0 PJ hydrogen)**
   Using recycled plastic as a feedstock, is an interesting option to create a closed and circular carbon cycle. It might also be part of the solution for the plastic waste problem. Looking at the McKinsey report about the world-wide plastic recycling potential, the virgin feedstock needed in 2050 will reduce with approximately 50%[16]. There might be a small hydrogen need to get the recycled products on spec. However, this amount is neglected in this study.

5. **Keep using fossil sources (0 PJ hydrogen)**
   When all petrochemical products are recycled, virgin feedstock is only used for the increase of plastic in the cycle. In this closed cycle the feedstock does not emit any greenhouse gasses.

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[12] ISPT Coresym report
[13] CBS Aardolieproductenbalans
[14] CBS Aardolieproductenbalans
[15] WGS: $CO_2+H_2 \rightarrow CO+H_2O$ and FT: $CO+2H_2 \rightarrow (-CH_2-) + H_2O$
[16] https://www.nrk.nl/Content/Files/file/Downloads/McKinsey%20Plastics%20Recycling_conference.pdf

Therefore, it is an option to keep using fossil-based feedstock. Although not evident, when there is no demand for fossil fuels in mobility this can result in high feedstock prices for the petrochemical industry.

Low hydrogen scenario:
In this scenario 50% of the plastics are produced by recycling, the need for virgin feedstock is fulfilled either by biomass or fossil sources. This leads to 0 PJ of hydrogen consumption.

High hydrogen scenario:
The need for feedstock can be fulfilled by recycling for 50%. This is also assumed to take place in high hydrogen scenario. The amount of virgin feedstock is covered by CCU and hydrogen. The need for hydrogen will be 50% of 520 PJ → 260 PJ.

When extrapolated to the crackers' demand, in the ARRRA there will be an extra 660 PJ of hydrogen needed for this market.

Heat demand

The petrochemical, excluding fertiliser and methanol, currently consumes 265 PJ of non-feedstock energy, out of which around 40 PJ is used as electricity. The major demand of heat is for high temperature applications (58%), followed by medium temperature (27%) and rest for low temperature applications (CE Delft, 2015).

1. Low temperature heat (100-250°C)
   Around 15% or 35 PJ of low temperature heat is used. This is small compared to the energy use for high temperature heat. Therefore, it is expected this heat demand can be filled in by residual heat, maybe in combination with heat pumps or MVR technologies. No hydrogen applications are expected in this temperature range.

2. Medium temperature heat (250-500°C)
   This temperature regime uses 27% or 60 PJ of the total energy demand. These temperatures can be produced by electric, biomass or hydrogen solutions.

Interview insights:
For the plastic industry not only CO_2 but also plastic waste is problematic. Increasing the recycling amount is beneficial for both the issues, and therefore, very interesting for this industry. Building a green value chain can be an important driver for CO_2 neutral plastics. A carbon added tax could help, by making products with a low carbon footprint cheaper to accelerate the transition.

For feedstock, this industry is looking at possible routes of recycling or biomass and hydrogen. The heating systems will most probably be electricfied, maybe in combination with hydrogen for peak demand and to ensureflexibility. The industry already posesses experience of using up to 70% of hydrogen in boilers to fulfill the heat demand.

3. High temperature heat (>500°C)
   The major part of energy use in this sector is for high temperature heat applications, 58% of total corresponds to 130 PJ. This energy is used to heat the feedstock which goes into the steam cracker. In all the mentioned feedstock alternatives the cracker is still needed in the process. Electricity is still technically difficult for these temperatures which leaves biomass or hydrogen as the possible alternatives.

The low and high scenario for industrial heating demand is calculated using IN2050 modelling in chapter 5.

4.1.4 Feedstock and heat for steel production

In the steel production process, most of the energy is used to reduce iron from iron ores in a blast furnace. The route to sustainable steel is likely through the HIsarna process which reduces CO_2 emissions on the shorter run and on the long run a CO_2 free process using hydrogen (DRI).

In the Netherlands, Tata Steel IJmuiden is the only steel producing industry, they report to produce around 7 million tons of steel a year using 19.6 GJ/ton of crude steel[17]. The total energy used for both feedstock and heat is 140 PJ. Based on the current coal throughput for steel production in Germany, Rotterdam provides the feedstock for roughly 3 times[18] the Dutch production.

Feedstock demand and alternatives

The steel production has the following carbon neutral alternatives:

1. **Hydrogen direct reduction process (40 PJ of hydrogen)**
   Hydrogen is used for the feedstock part and an electric arc furnace is used for heating. The energy need is the following:
   - H_2 as feedstock: 6,1 GJ/ton[19] iron
   - Electric heating: 4,2 GJ/ton iron

   This leads to a hydrogen feedstock demand of 40 PJ.
2. More **recycling** of steel scrap, which is possible in the DRI process, will decrease the amount of hydrogen needed.
3. **CCU** using the current cokes-based process **(0 PJ of hydrogen)**
   Following the plans developed in the CORESYM study the emissions of steel production can be used as feedstock for the chemical industry. In this case the steel process does not need any hydrogen but as described at section 4.1.3, in petrochemistry the total chain will consume 43 PJ of hydrogen.

[17] Sustainability report Tata Steel in the Netherlands 2015/2016
[18] https://www.deltalinqs.nl/stream/kolen.pdf
[19] Assessment of hydrogen direct reduction for fossil free steelmaking, Valentin Vogl

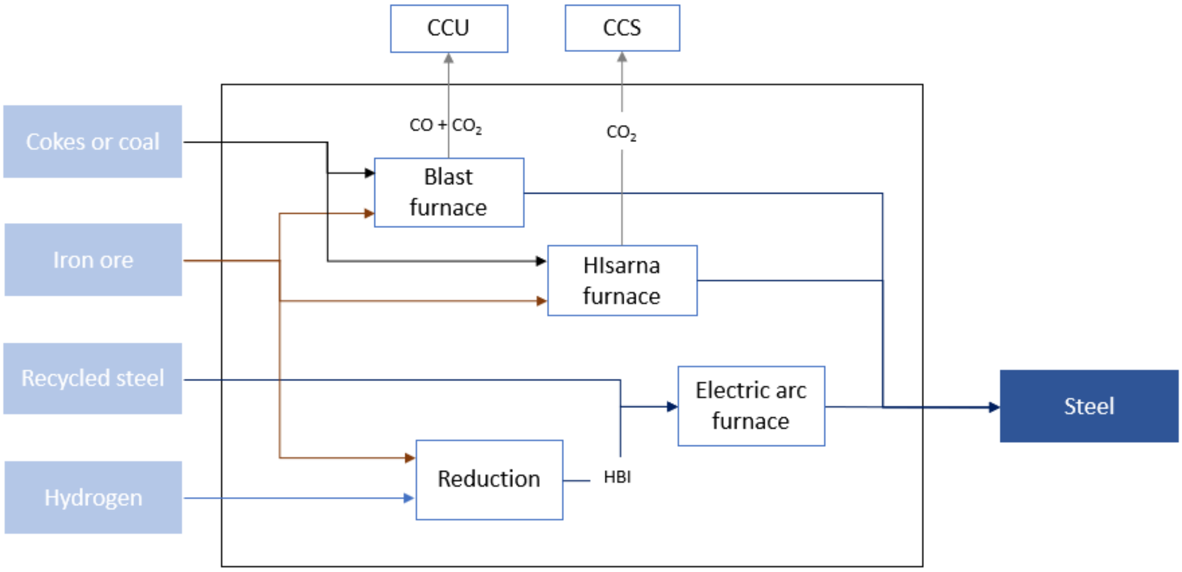


Figure 13: Identified routes for steel production

4. **HIsarna combined with CCS (0 PJ of hydrogen)**
   Because the HIsarna process emits very pure CO_2 this is likely to be stored easily in a nearby gas field. This process is based on cokes and there will be no need for hydrogen.

Low hydrogen scenario:
In the low hydrogen scenario, the HIsarna process in combination with CCS is the preferred route. The other options either DRI or CCU, both involve demand of around 40PJ of hydrogen.

High hydrogen scenario:
For the high scenario, the direct reduction of iron ore using hydrogen will be the envisaged production method. The hydrogen demand of this process is about 40 PJ.

Heat demand
The heat demand changes significantly when a hydrogen feedstock alternative is used (high hydrogen scenario). In this case the largest heat demand (4,2 GJ/ton steel) is electrical using an electric arc furnace to produce crude steel from DRI. The ore heating process which uses roughly 1,5 GJ/ton of steel, could be done using hydrogen or biomass. The yearly energy consumption for this process is 10 PJ. As the heat demand is highly specific to process that will be adopted in future, the IN2050 modelling does not take this sector into account to estimate future energy mix of the industry sector in the Netherlands.

4.1.5 Heat for Non-metallic minerals
The sector has a major demand for high temperature heat applications. The total energy consumption is 24 PJ, of which, 4 PJ is electricity. The remaining 20 PJ is used for high temperature heat production with temperatures over 500°C. In this temperature range both hydrogen and biomass can be used.

4.1.6 Heat for food industry

Final energy consumption of the food sector is 86 PJ, out of which 23 PJ is used directly as electricity. The sector consumes 50% of its heat for low temperature applications (100- 250C) and 50% for applications requiring <100C (32 PJ). The sector mainly consumes heat in the form of steam (for process like distillation and drying).

Potential alternatives:

- **Direct electric heating**: Electric boilers could potentially replace gas boilers in this sector given that the temperature requirement of this sector is feasible with electric boilers. Yet the consequences are an increasing electricity demand, more backup capacity/storage and substantial increase in transmission capacity/grid electricity.
- **Geothermal**: Ultra deep geothermal with depths exceeding 4000 metres can be an alternative. However, the technical feasibility of the system is very site specific. Societal acceptance and geological risks play major roles in acceptance of UDG. Further, success rate is not predictable as it depends mainly on subsurface conditions.
- **Biomass**: Biomass provides opportunity to reduce CO2 emissions. However, it is crucial to have the guarantee on sustainability of biomass as well as limit in GHG emissions across the supply chain.
- **Hydrogen**: The technology to use hydrogen in burners are already available but is not economically attractive against current alternatives
- **Heat pump upgrading waste heat**: Heat pumps are very efficient but have not yet reached the desired temperature.

The low and high scenario for industrial heating will be calculated using IN2050 modelling in chapter 5.

4.1.7 Heat for paper production

The final energy consumption of paper sector is 24 PJ, out of which electricity demand is 9 PJ. The remaining 15 PJ is for heat production. All heat is used in the temperature range of 100-250C. The paper industries in the Netherlands have earlier made major investments in CHP units to meet their demand. However, several units were decommissioned in past years due to unfavourable gas and electricity prices

Possible alternatives are the same as that for the food sector due to similar heat/steam requirements for this sector.

4.1.8 Refineries

Refineries are a special sector when looking at scenarios for the energy transition. When fossil sources are phased out there will be no need for refineries. For all the alternatives described in the previous sections only feedstock for petrochemistry has the possibility for using fossil sources. The refineries might switch to synthetic fuel production. In this study the heat and hydrogen demand of this sector is not considered.

Because of the current hydrogen use in refineries they could provide the first offtake of hydrogen. In this way refineries can be an important starting point for a hydrogen cluster.

4.2 Built environment and agriculture

4.2.1 Built environment

The built environment uses a total of 460 PJ of energy for heat. This can be divided in the following main categories[20]:

- The total 7,5 million houses and apartments in the Netherlands use 260 PJ for heating and 52 PJ for hot water
- Non-residential buildings use 148 PJ for heating purposes

There are quit some carbon neutral alternatives for the heat demand since the needed temperature is low (~80°C) to ultra-low (~40°C). But, due to the variety of different buildings and different owners there is no easy solution for this heating demand. Probably different types of buildings will be supplied differently, also depending on the location.

The following options are considered:

1. Heat grid connection; multiple sources or a combination of sources in peak and baseload is possible
    a. Industrial residual heat
    b. Geothermal heat
    c. Central biomass boiler
    d. Central heat pump
    e. Hydrogen boiler, most likely for peak demand
2. Bio or green gas replacing natural gas
3. All electric using a heat pump, only applicable for new or very well insulated buildings
4. Hybrid heat pump with hydrogen for peak demands and higher temperatures

Low hydrogen scenario:

For the Low scenario no hydrogen demand is identified. Due to many alternatives the use of hydrogen in this sector is not certain.

High hydrogen scenario:

This High hydrogen scenario is determined by using the energy transition model. This results in a total hydrogen demand of 40 PJ:

- Based on the Hoogeveen study, around 1 million houses in the Netherlands are unsuitable for all electric and heat distribution networks. These are expected to use a hybrid heat pump in which 20% of the energy is provided by hydrogen, this corresponds to 10 PJ hydrogen demand.
- Another 30 PJ is used as peak supply in heat grids combined with for instance geothermal heat.

[20] Quintel Energy Transition Model

4.2.2 Agriculture

The agricultural sector has a final energy demand of 120 PJ. This is all for low temperature (<100°C) heat mainly for greenhouses. The alternatives are similar to solutions in residential areas.

Low hydrogen scenario:

For the Low scenario no hydrogen demand is identified. Due to the many alternatives the use of hydrogen in this sector is not certain.

High hydrogen scenario:

This High hydrogen scenario is determined by using the energy transition model. This results in a total hydrogen demand of 14 PJ due to peak demand in combination with other heating solutions.

4.3 Mobility

4.3.1 Passenger transport

For passenger transport, cars and busses, a total of 112 PJ of hydrogen is needed to replace all the current fuel [21]. The efficiency differences of petrol and hydrogen mobility are taken into account by the ETM. All cars need 105 PJ of hydrogen and all busses need 7 PJ of hydrogen. For this part of mobility, a clear alternative is electrifying cars and busses.

Low hydrogen scenario:

This part of mobility can run fully on electricity, so in the Low case the amount of hydrogen in zero.

High hydrogen scenario:

In this scenario, hydrogen will be used for half of the passenger kilometres as we estimate that half of the kilometres can be accounted for short distance travel that will be filled in with electric power and that all busses will use H_2. This results in 60 PJ of hydrogen.

4.3.2 Freight transport

The total freight transport in the Netherlands would need a yearly total of 145 PJ hydrogen. Trucks represent 130 PJ of this demand and inland ships would need 15 PJ of hydrogen. For freight transport the following alternatives are identified:

1. Biofuels, using current engines and fuel infrastructure
2. Electric powered, especially relevant when battery technology improves
3. Hydrogen, multiple carriers are possible, liquid, compressed, etc.

Low hydrogen scenario:

Due to the alternatives, the low scenario does not include any hydrogen. Biofuels can be used for longer distances and electric within cities.

High hydrogen scenario:

For the High scenario the full transport sector uses hydrogen. This can be caused by the price of biofuels or regulation on local emissions like NO_x or noise. This would result in a hydrogen demand of 145 PJ.

[21] Quintel Energy transition model

4.3.3 Fuels for aviation

The total energy bunkered in the Netherlands for aviation fuels is 160 PJ. This amount is not accounted for in the Paris agreement, but should also be decarbonise in light of climate change.

Due to safety considerations, aviation will likely keep using kerosene in 2050. This fuel can be produced in a sustainable way:

1. Biofuels can be used as substitute for kerosene
2. Synthetic fuel produced using hydrogen and green CO_2. The need for hydrogen in this case will be higher compared to direct use. When an energy efficiency of 70% is assumed for the synthetic fuel production, a total of 230 PJ hydrogen is needed.

Low hydrogen scenario:

Aviation will not use any hydrogen, either because biofuel is the preferred source or synthetic fuels are imported from other countries.

High scenario:

When the synthetic fuel is produced in the Netherlands there will be a need for 230 PJ of hydrogen. This does imply the use of a green CO_2 source, for instance direct air capture because carbon emissions from aviation are still present and needs to be compensated.

4.3.4 Fuels for international ships

A total energy amount of 500 PJ is currently bunkered in the Netherlands. For decarbonisation, there are possible following options:

1. Use hydrogen directly or through a hydrogen carrier like ammonia
2. Biofuels can be a substitute using the same engines

Low scenario:

In this scenario no hydrogen is used because this sector uses biofuels.

High scenario:

All the current fuel need is replaced by a hydrogen product, this corresponds to a need of at least 500 PJ hydrogen.

Table 1: Overview of possible H2 demand in 2050: interviews and literature studies

Sector	Low H2 demand	High H2 demand
Industrial feedstock		
• Fertilizer	68 PJ	68 PJ
• Methanol	0 PJ	20 PJ
• Petrochemistry	0 PJ	260 PJ
• Steel	0PJ	40PJ
Built environment & Agriculture	0 PJ	54 PJ
Mobility		
• Passenger transport	0 PJ	60
• Freight transport	0 PJ	145
• Aviation fuels	0 PJ	230
• Marine fuels	0 PJ	500
Total	**68 PJ**	**1377 PJ**

5. Industrial heat: IN2050 model

The previous chapter provided an overview of possible H2 demand in: industrial sector (for feedstock), built environment & agriculture and mobility sectors.

In this section, the potential of hydrogen as fuel for industrial heating has been estimated under the three scenarios; base (based on current and proposed policies), low and high H2 demand scenarios.

The potential demand is modelled using IN2050 scenario tooling in which share of H2 is determined by its merit order against other CO2 neutral heating systems (like biomass boiler, electric boiler, deep geothermal etc.)

IN2050 methodology is depicted in 0. The results are discussed in a broader context for the entire industrial sector of the Netherlands in this chapter.

5.1 Introduction

A set of assumptions in 2050, for each scenario (ex: fuel prices indexation) are taken as inputs to the model. The indexation is varied in different scenarios to test the sensitivity of H2 demand (with respect to the major tipping points). Finally, results of all the scenarios are discussed in detail to give insights on dynamics of energy mix (specially on Hydrogen) for industry sector.

Table 2 Assumptions on current fuel prices (2015)

	Units	Base line- 2015	Reference/Assumptions
Natural Gas	€/Nm3	0,15	NEV 2017- ECN, PBL, RVO
Hard Coal	€/ton	46	NEV 2017- ECN, PBL, RVO
Biomass Pellet	€/ton	170	WLO, 2016
Electricity Wholesale Price	€/MWh	41	NEV 2017- ECN, PBL, RVO
H2	€/kg	1,50	CE Delft, 2018
Oil	USD/barrel	47	NEV 2017- ECN, PBL, RVO
CO2 ETS	€/ton	5	NEV 2017- ECN, PBL, RVO

5.2 Base Scenario

Potential demand of H2: 124 PJ

Based on:

- Nationale energie verkenning 2017[22]- established and proposed policies
- Toekomstverkenning welvaart en leefomgeving 2015[23]

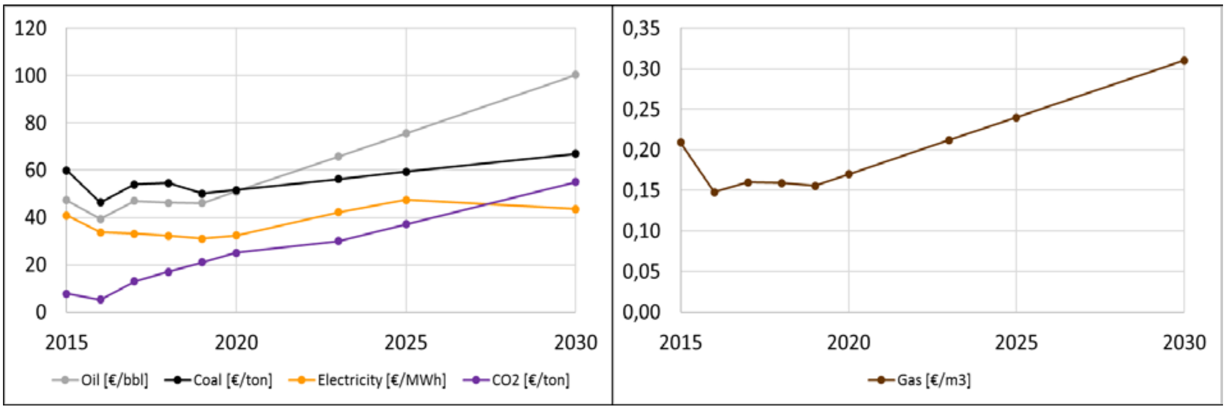


Figure 14: Trends in fuel prices for base scenario (NEV 2017- ECN, PBL, RVO). CO2 ETS price[24]

- Trends are extrapolated to 2050
- CO2 ETS price assumed to increase to 55 €/ton in 2030.[24]
- Wholesale price of electricity is assumed to be 50 €/MWh in 2050.
- Estimation on trend in H2 price is shown in Annex E: 3 €/kg in 2050.

[22] https://www.pbl.nl/publicaties/nationale-energieverkenning-2017
[23] https://www.wlo2015.nl/wp-content/uploads/PBL_2015_WLO_Nederland-in-2030-en-2050_1558.pdf
[24] https://www.carbontracker.org/eu-carbon-prices-could-double-by-2021-and-quadruple-by-2030/

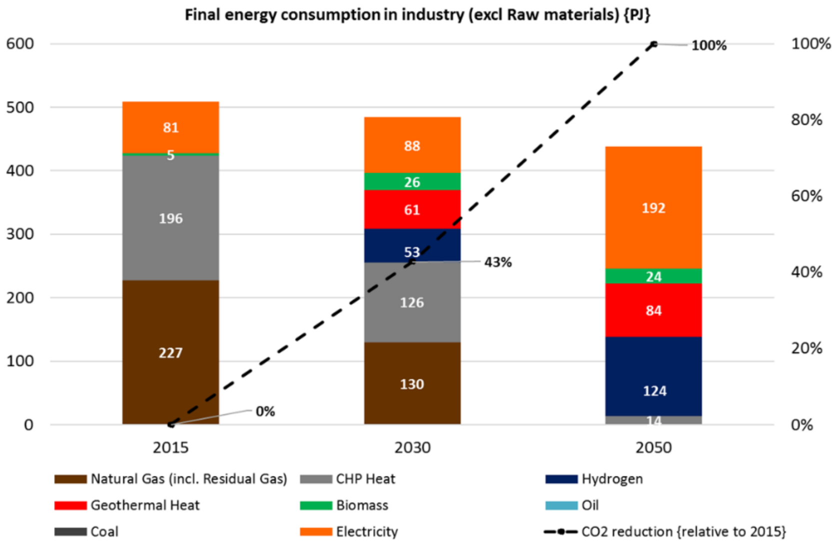


Figure 15: Base scenario- Evolvement of energy mix in industrial

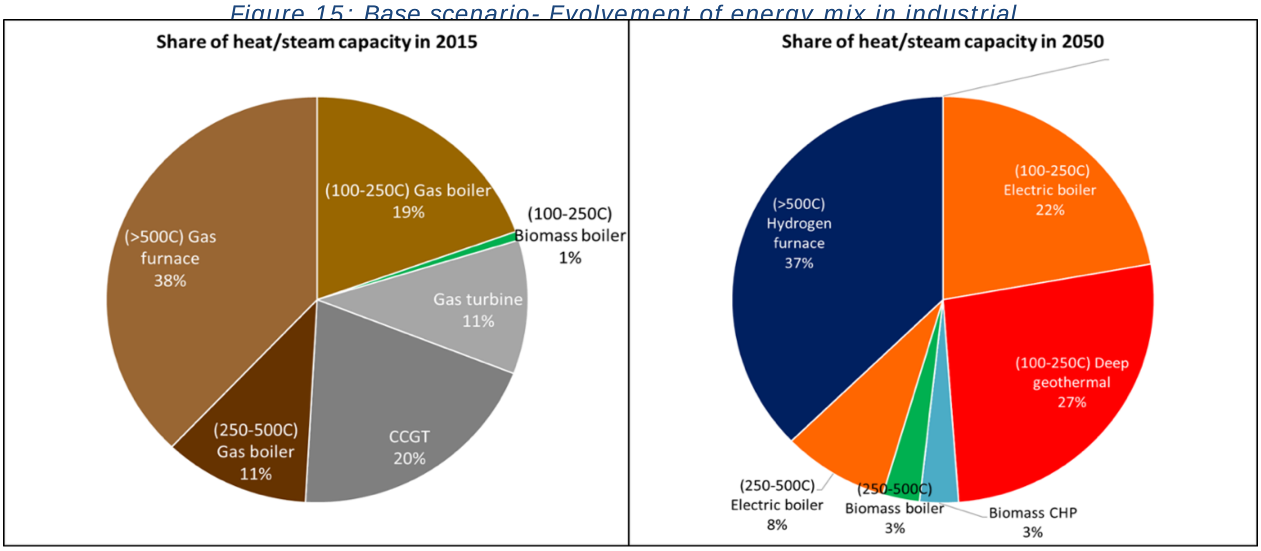


Figure 16: Base scenario- Share of thermal capacity by different energy systems in 2050 against 2015

Key findings:

- Hydrogen in HT applications- the largest demand of hydrogen for this scenario is for applications with high temperature range of more than 500 C, specifically in petrochemistry sector. Use of hydrogen in medium and low temperature ranges was very limited as electric options and ultra deep geothermal (with heat upgradation using heat pump) became financially more attractive.
- Electrification of heating system was economically attractive (both in terms of investment cost and operating cost-@ 50 €/MWh wholesale power price) for LT steam/heat production. Thereby, the demand of electricity increased more than twice as compared to current demand.
- Ultra deep geothermal with heat upgradation technologies (like steam heat pump and MVR) competed against electric boilers for base load heat supply at LT range. The potential heat demand by UDG could rise to 84 PJ by 2050.

5.3 Low Case Scenario

Potential demand of H2: 28 PJ

Under the low case scenario, minimum demand of hydrogen till 2050 is forecasted. In the previous scenario, hydrogen played a key role for HT furnace. Potential competitors for hydrogen could be; biomass furnace and electric arc furnace. For this scenario, the impact of *biomass price* on biomass demand as well as H2 demand are analysed. Further; the wholesale price of electricity was kept same as in the previous scenario at 50 €/MWh.

Based on:

- Assumptions on fuel prices are same as that in base scenario except for biomass
- Biomass price is kept constant at current level (2015) with no change in price in coming years. This is based on an assumption that globally enough biomass will be available to fulfil the demand until2050 with minimal repercussion on the price.

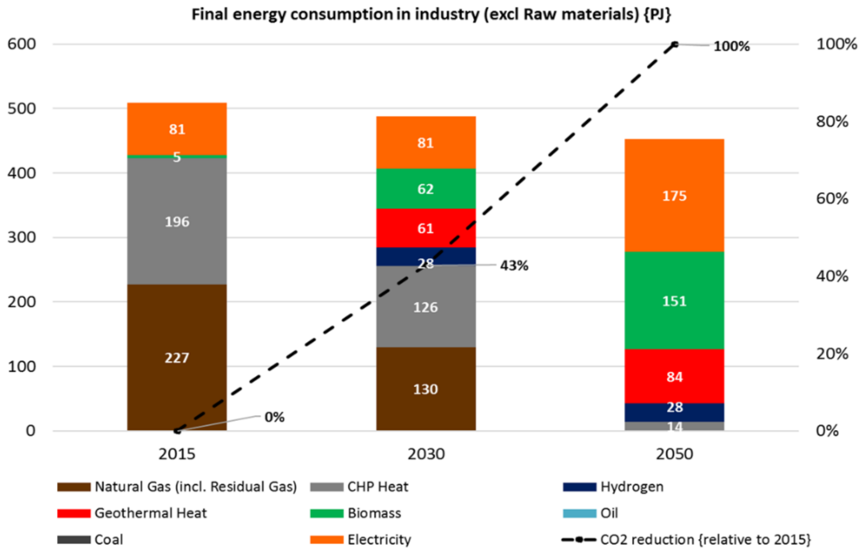


Figure 17: Low case scenario- Evolvement of energy mix in industrial sector including electricity use for non-heating purpose

Key findings:

- Under this scenario, biomass furnace took over a major share from hydrogen furnace as it is economically more attractive owing to lower operating cost (fuel cost). The application of biomass is majorly in high temperature range followed by a small share in low temperature range as shown in Figure 18. However, the availability of sustainable biomass is a controversial topic which

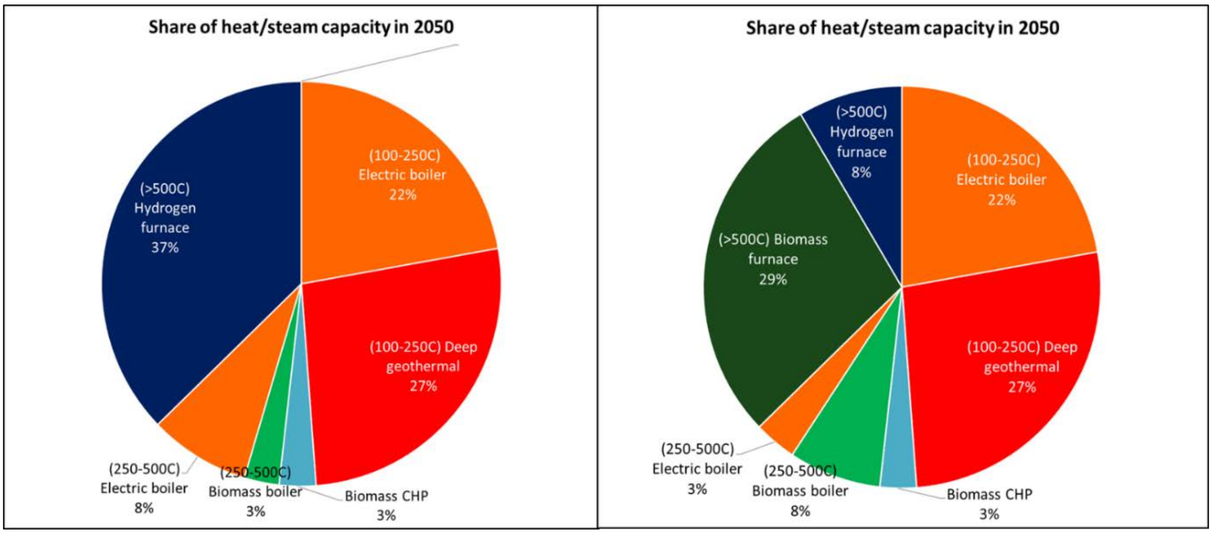


Figure 18:Base scenario vs Low case scenario- Share of thermal capacity by different energy systems in 2050

has a significant impact on demand of hydrogen. This tipping point is discussed in detail in section 6.4.

- Electricity demand is 10% lower in this scenario, as biomass boiler for MT range has a bigger share as compared to the base scenario.
- The demand for H2 is only limited to 28 PJ, with a small share in HT range as shown in Figure 18.

5.4 High case scenario

Potential demand of H2: 255 PJ

The aim of this scenario is to forecast possible high demand for hydrogen with focus on tipping points: *whole sale electricity price and hydrogen price.* As electricity and deep geothermal, owned major share in LT heat; in this scenario it has been analysed how H2 can become economically attractive for low temperature range. Similar analysis is done for medium temperature range.

5.4.1 High case scenario 1: High Average electricity price

Potential demand of H2: 124 PJ

Under this scenario, it is assumed that the wholesale electricity price for industry reaches to 100 €/MWh in 2050. Further, it is assumed that the trend in H2 price remains same as in base scenario, i.e. green H2 is produced from north shore wind electricity price at 50 €/MWh.

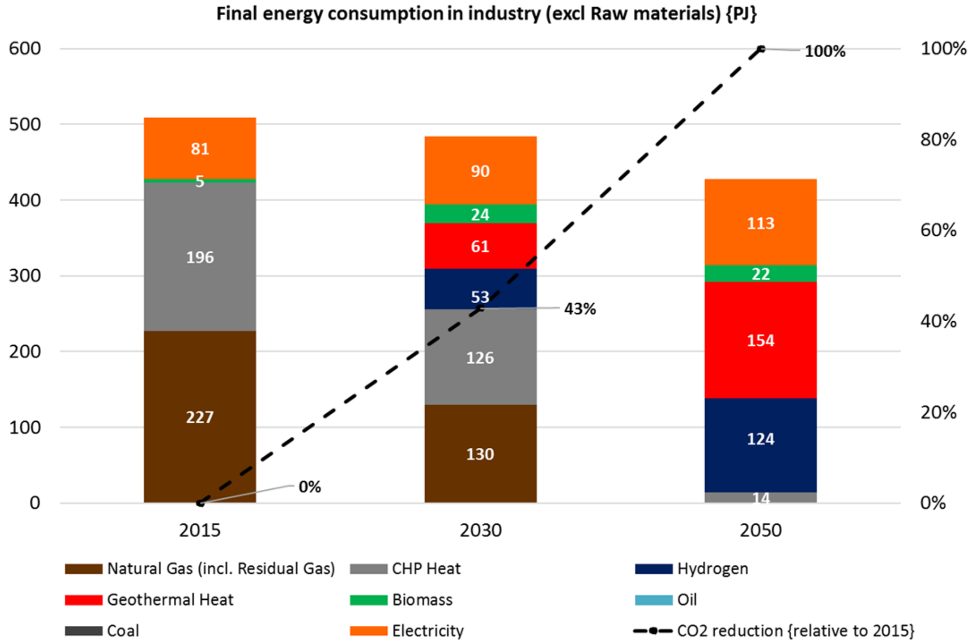


Figure 19: High case scenario 1- Evolvement of energy mix in industrial sector including electricity use for non-heating purpose

Key findings:

- The demand for H2 remains same as that in base scenario limiting its application to high temperature range only.
- As shown in Figure 20, almost entire LT heat is provided by ultra deep geothermal. The potential of geothermal in this scenario is 2x than in base scenario. Although, the operating cost of geothermal increases with increase in electricity price, it is still economically more attractive as compared to hydrogen or biomass.

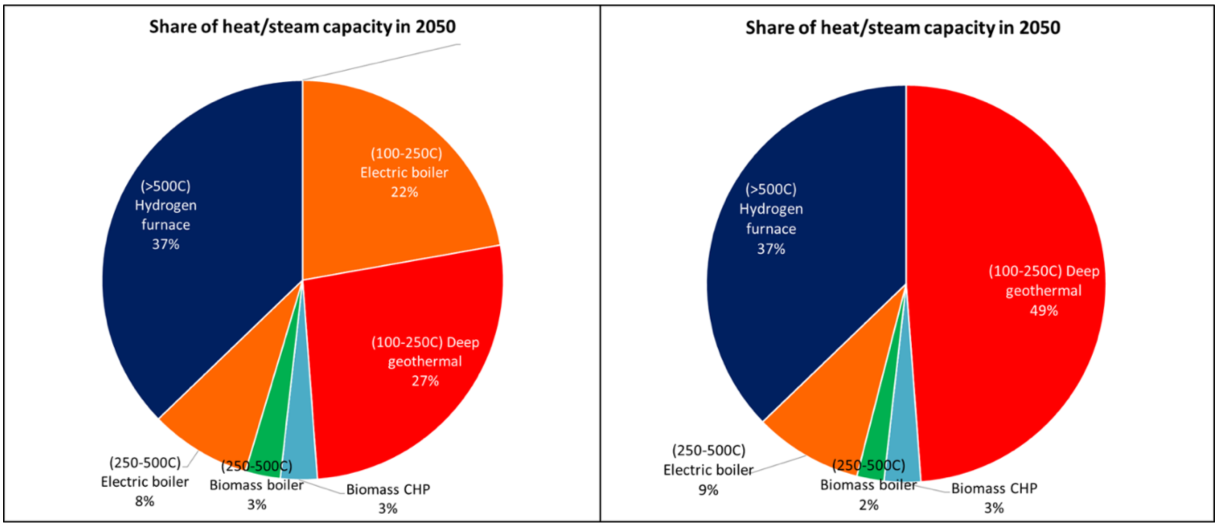


Figure 20: Base scenario vs High case scenario 1- Share of thermal capacity by different energy systems in 2050

5.4.2 High case scenario 2: Constant H2 price

Potential demand of H2- 255 PJ

Under this scenario, it is assumed that the wholesale electricity price for industry reaches to 100 €/MWh in 2050 and price of H2 remains constant at 1,5 €/kg (current production cost of grey hydrogen) until 2050. Thereby, this scenario is not based on an actual price assessment (blue and green H2 cost development) rather, it investigates the sensitivity on hydrogen demand based on current price.

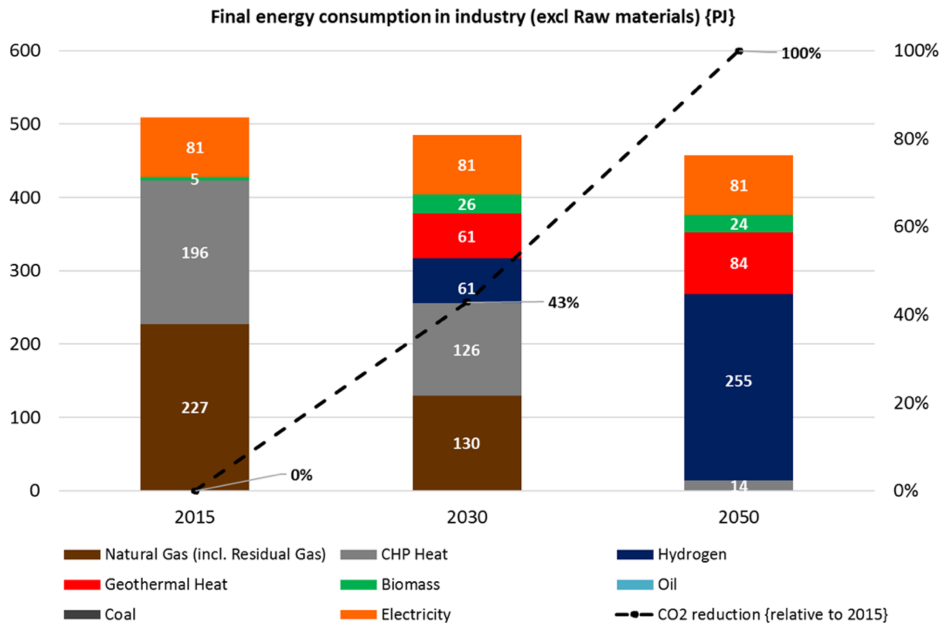


Figure 21: High case scenario 2- Evolvement of energy mix in industrial sector including electricity use for non-heating purpose

Key findings:

- The demand for H2 increases by 2x in this scenario as compared to the base scenario (Figure 21). Figure 22, depicts the rise in share of hydrogen in LT and MT ranges, as it becomes economically more attractive, compared to electric and biomass counterparts.
- Demand of electricity remains constant at current level (only for non-heating purpose). Hence, in this scenario electrification of industry for heating purpose is economically unattractive.

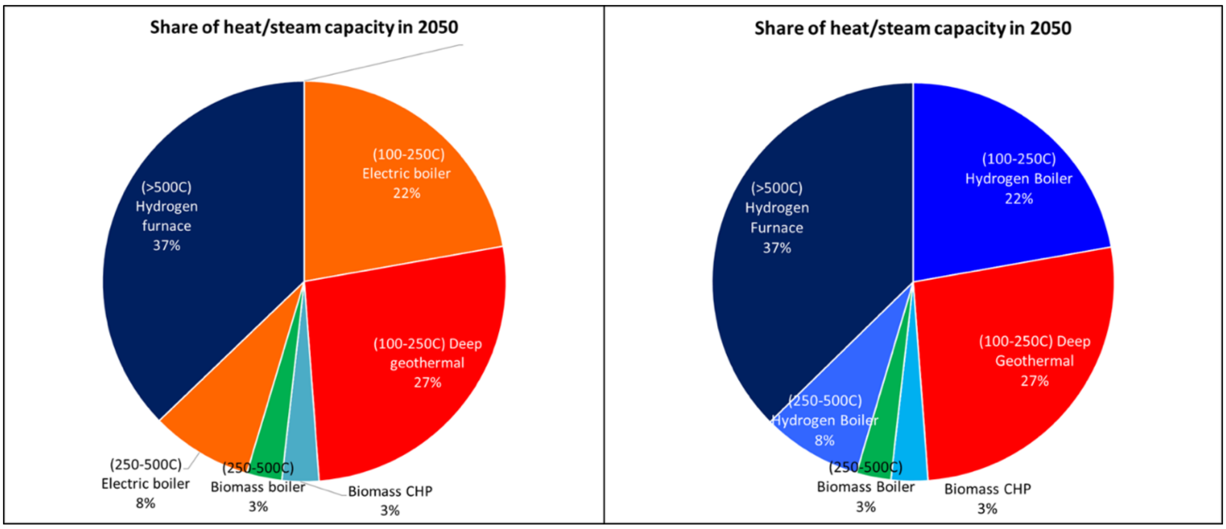


Figure 22: Base scenario vs High case scenario 2- Share of thermal capacity by different energy systems in 2050

Table 3: Overview of possible H2 demand in 2050: interviews, literature studies and IN2050

Sector	Low H2 demand	High H2 demand
Industrial feedstock • Fertilizer • Methanol • Petrochemistry • Steel	 68 PJ 0 PJ 0 PJ 0PJ	 68 PJ 20 PJ 260 PJ 40PJ
Industrial heat	28 PJ	255 PJ
Built environment & Agriculture	0 PJ	54 PJ
Mobility • Passenger transport • Freight transport • Aviation fuels • Navigation fuels	 0 PJ 0 PJ 0 PJ 0 PJ	 60 145 230 500
Total	**96 PJ**	**1632 PJ**

6. Major tipping points

From the previous chapter, it was concluded that when all the scenarios are combined, a huge spread between the possible high and low scenarios is envisaged. This is because many alternatives are available for different applications. In this chapter, we have identified the most important tipping points and their corresponding impact on hydrogen demand.

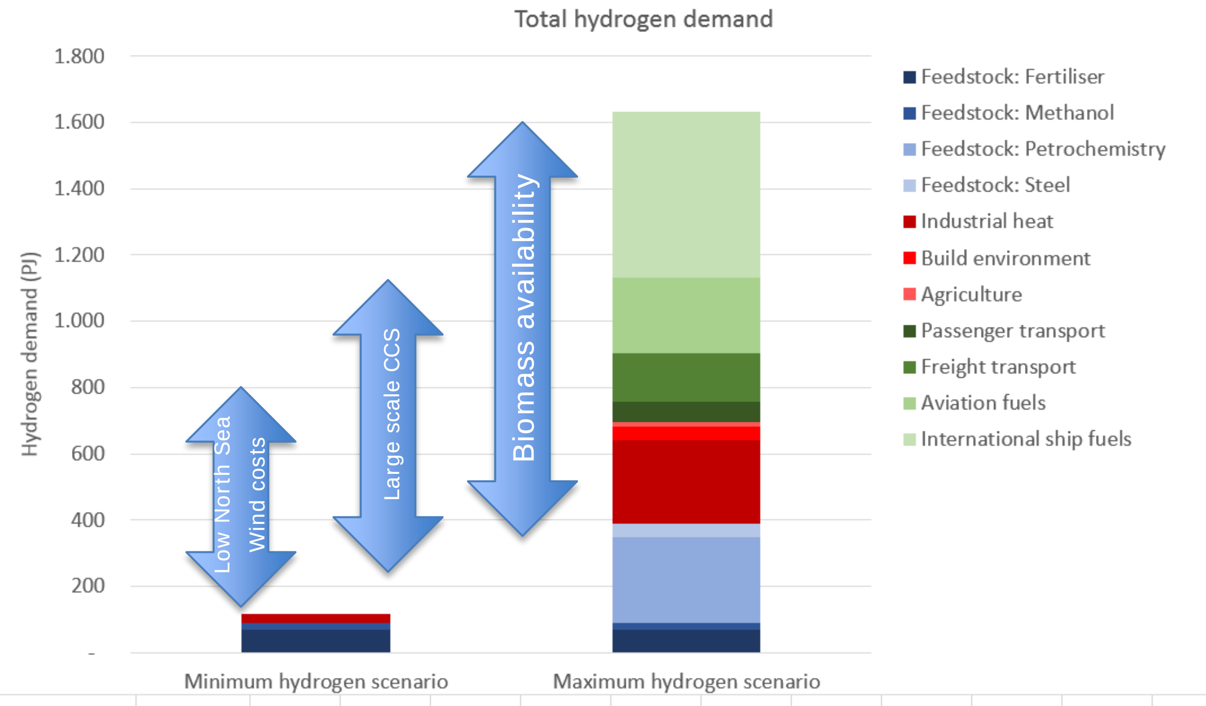


Figure 23: Hydrogen demand in two scenarios and the tipping points giving the order of magnitude of their influence on the hydrogen demand.

6.1 Overview

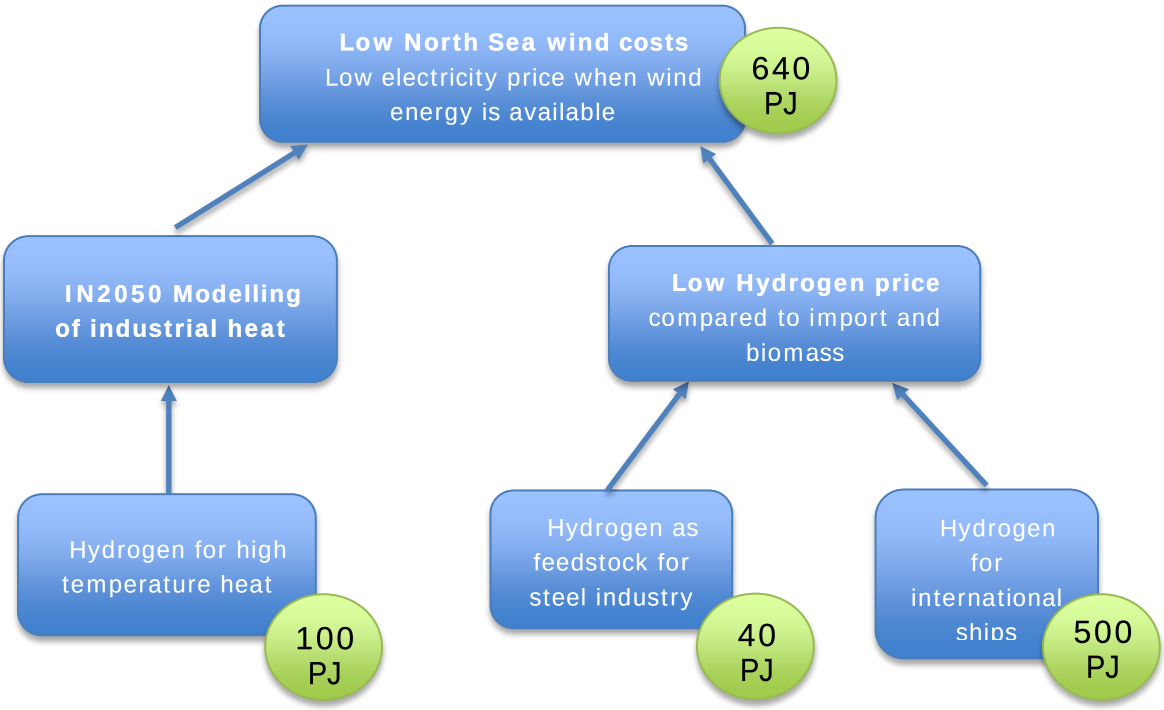
In Figure 23; hydrogen demand of two scenarios is depicted. Also, the three major tipping points are visualised with their corresponding influence. The reasoning and argumentation are explained in the next section, a summary is given below:

1. **Availability of biomass** *(influences 1100 PJ of hydrogen)*
   Biomass is an interesting option for industrial feedstock and heating processes. When the biomass supply is very limited for many processes' hydrogen is potentially, the only option left. It influences: methanol production, virgin feedstock for petrochemistry, fuels for international ships, aviation fuels and high temperature heat.
2. **Large scale CCS possible and accepted** *(influences 890 PJ of hydrogen)*
   The assumption is that when CCS is possible and accepted, year on year increase in price of hydrogen will be low (grey→blue→green). In this case, the functionalities in various sectors which do not use any carbon for feedstock or fuel are considered to use hydrogen.
3. **Low North Sea wind costs** (influences 640 PJ of hydrogen)

In this case both hydrogen (green) and electricity are relatively cheap. For heating processes, the IN2050 model shows only a part of H2 demand will be influenced (section 5.4). Another important factor is hydrogen for international shipping. For this application, no electric alternative is possible.

6.2 North Sea wind costs

The Netherlands have a unique location for off shore wind with a large coast, and relatively a large part of the North Sea continental shelf. The North Sea is shallow and therefore, ideal for cost effective off shore wind implementation. This tipping point becomes relevant when costs of energy from North Sea wind are low compared to other countries and biomass. The figure below shows schematically; the influence of the tipping point (with order of magnitude for hydrogen demand).

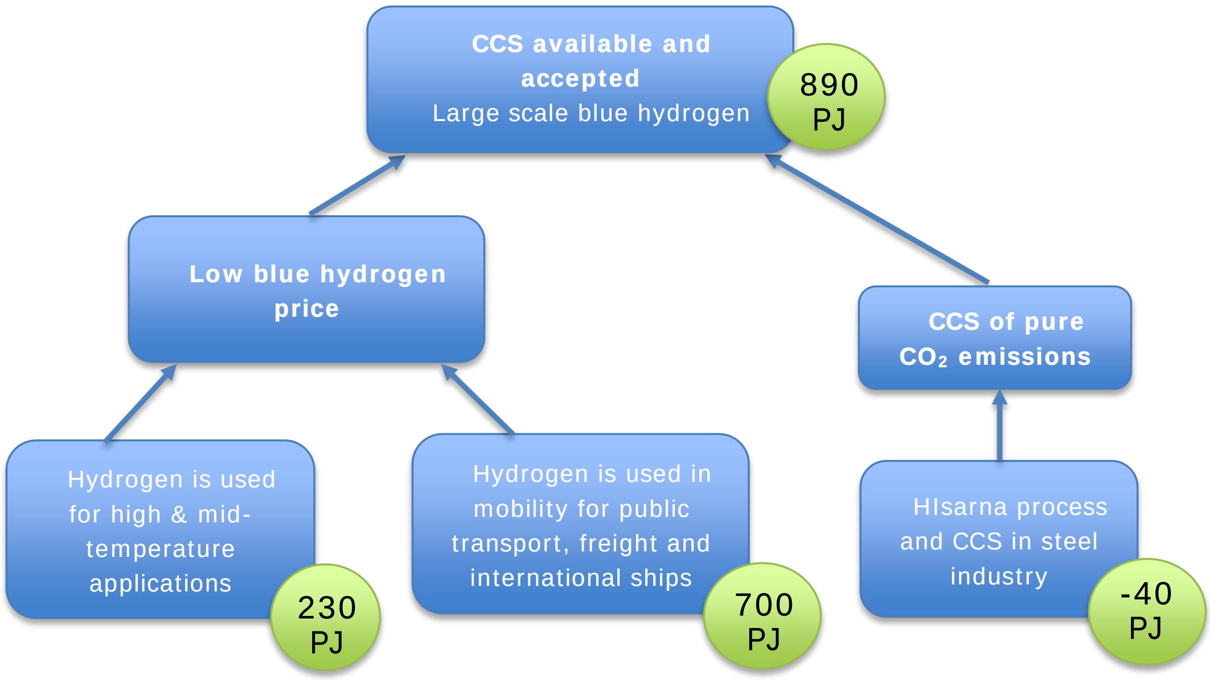


In order to estimate the potential of hydrogen demand influenced by this tipping point, the following argumentations are used:

- Low North Sea wind costs result in low electricity and hydrogen prices.
    - For feedstock uses; all non-carbon use of feedstock is directly influenced by this tipping point. If carbon is in the feedstock the availability of a carbon source is probably more important. Only steel and fertiliser industry use hydrogen as feedstock without carbon, since fertiliser industry uses hydrogen in any scenario, the influenced part is 40 PJ from the only steel industry.
    - In mobility, hydrogen options are preferable but because the cost of electricity is also low only the mobility with no electric option is added. Also, aviation fuels are left out because the development of other processes like direct air capture and Fischer-Tropsch is of more influence. Only hydrogen for international shipping is clearly influenced by this tipping point representing 500 PJ of hydrogen
- In the IN2050 modelling tool this tipping point is calculated for industrial high temperature heat using a difference between average electricity whole prices and low electricity prices for hydrogen production. As described in section 5.4.1, this results in an extra hydrogen demand of 100 PJ (on top of low scenario demand of 28 PJ).

6.3 Availability and acceptance of CCS

Not everyone sees carbon capture and storage as a solution for decarbonisation. It can slow down innovations and is envisaged as a temporary transition technology. But it can also provide a kickstart to hydrogen solutions. The production of hydrogen from natural gas gives almost pure CO_2 (ex: ATR process) which can easily be stored. If this is an accepted method of creating a carbon neutral energy carrier and feedstock, it can influence the hydrogen demand in the order of 900 PJ.

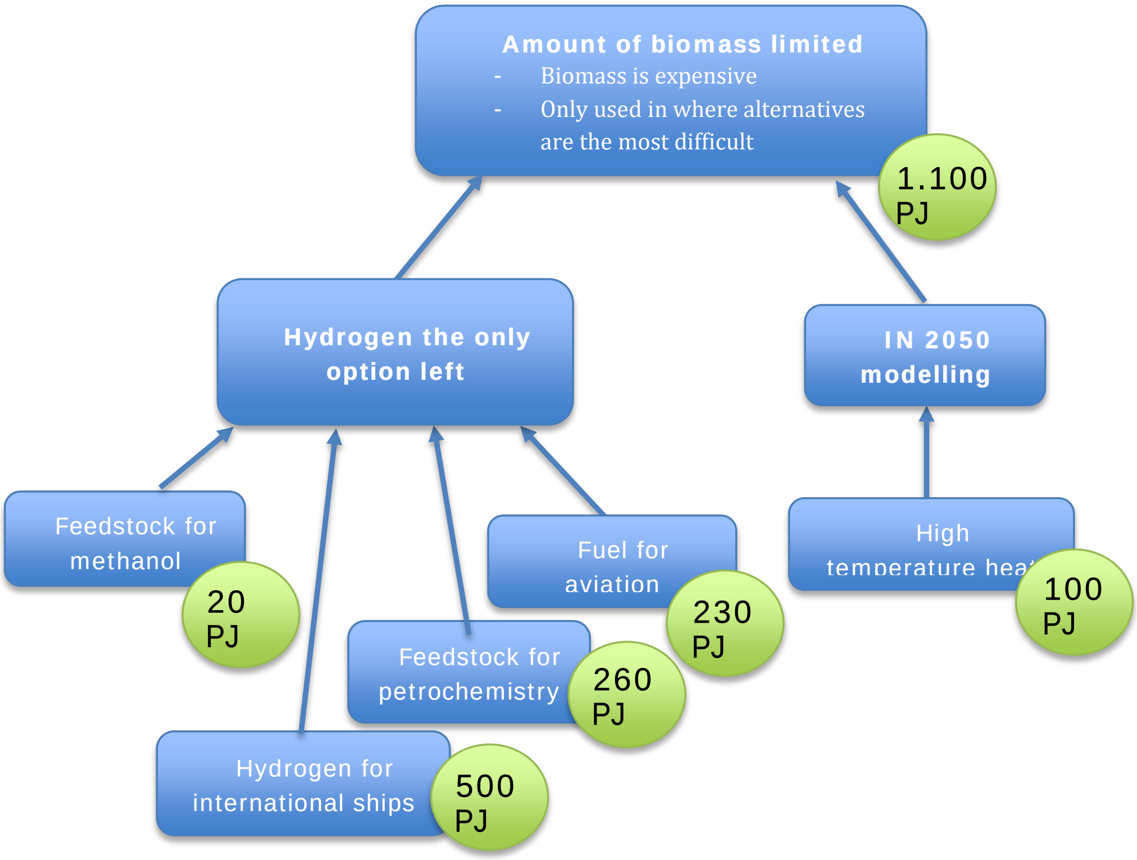


In order to estimate the potential of hydrogen demand influenced by this tipping point, the following argumentations are used:

- Processes which produce pure CO_2 will not use the hydrogen alternative but will use direct CCS. This is only true for the HIsarna steel production. A heating process for instance results in flue gas containing around 10% of CO_2, separating the CO_2 is difficult and cannot be done 100%. In these cases, it is probably easier to produce blue hydrogen for the use of heat production. The direct CCS results in -40 PJ of hydrogen because of the steel industry.
- The expected low blue hydrogen price has consequences for heating and mobility. In all the feedstock applications apart from steel and fertiliser industry the carbon molecules are needed. The availability of a green CO_2 source is in these cases more important.
  - For heating IN2050 modelling shows that with a constant low price for blue hydrogen 230 PJ of hydrogen is needed as described in section 5.4.2(on top of 28 PJ for low scenario).
  - With CCS, a large supply of CO_2 neutral hydrogen can become available on the short term. This will boost the use for hydrogen for all purposes where no electric alternative is available or practical. This gives the total hydrogen demand of passenger transport, freight transport and international shipping of 700 PJ.

6.4 Availability of biomass

Biomass is a possible alternative for almost every heating or feedstock demand. But the large-scale use of biomass is controversial. It is an open question: how much biomass we can use for energy production and feedstock without influencing food production whilst preserving nature. Therefore, it is also difficult to calculate the share available for the Netherlands. This tipping point shows the influence of a limited availability of biomass.



In order to estimate the potential of hydrogen demand influenced by this tipping point, the following argumentations are used:

- When biomass is limited, for the following applications restrict their use to hydrogen.
  - For methanol production, hydrogen in combination with a green carbon source is the solution when no biomass is available, 20 PJ of hydrogen is used.
  - Fuel for aviation must be made from hydrogen and a green carbon source, this results in 230 PJ of hydrogen.
  - For feedstock in petrochemistry, hydrogen with a green carbon source is the likely alternative when biomass is not available. The only other alternative is feedstock from fossil sources, but this is not considered as a long-term solution. The hydrogen demand will increase by 260 PJ.
  - For international shipping no alternatives other than biomass where identified. Therefore, this tipping point results in an extra 500 PJ of hydrogen demand.
- The IN2050 model shows that when biomass is relatively expensive, an increase of 100 PJ in hydrogen demand will occur (see sections 5.2 and 5.3: base scenario where projected

demand in 2050 of H_2 is 124 PJ where as in low scenario the demand is 28 PJ, giving a difference of about 100 PJ). The other heating demand is met by electric and geothermal solutions.

6.5 Some other tipping points

The other tipping points which also potential determine the demand of hydrogen are:

Performance of electric energy storage

By performance. a combination of cost decrease and technical improvement is meant. The technical factors will determine how the range of cars will develop and the possibility for applications in freight transport. When prices of electric storage become low enough to balance the electricity grid the electricity price will be less volatile. This stable electricity price will make electrical options for industry more interesting.

Government stimulation of green electricity supply

The increasing development of offshore wind instalment, further triggers opportunities for producing hydrogen offshore. This could significantly contribute towards stabilization of electricity grid. An important attribute to lower investment cost could be: usage of existing gas infrastructure for hydrogen transportation. Further, hydrogen production from offshore wind could provide benefits like; greater energy security and lower price volatility[25].

Safety perception of hydrogen in built environment (40 PJ)

The perception of society on use of hydrogen is a tipping point which influence the demand of H2 prominently, in the sector- built environment. The H21 project in Leeds, concludes that the necessary technology needed to cover the city to hydrogen is in place and has been proven successful. Hydrogen could not only play role for old houses with minimal insulation in the cities but also in the countryside.

In case, if hydrogen is not perceived safe- the demand of H2 will decrease by 40 PJ in 2050 for the built environment sector.

Development of Direct Air capture (influences 510 PJ of Hydrogen)

The development of direct air capture technology is also a key enabler, for boosting the hydrogen demand specifically for feedstock in the industries. In methanol industry, if the DAC is available then it can be used along with green hydrogen to produce methanol. However, if DAC is not available then CO2 from biomass can be alternate route. The potential of H2 with air capture could influence its demand up to 260 PJ in petrochemistry sector (section 4.1.3) and 20 PJ in methanol sector. Also, green CO2 source, is needed to produce synthetic fuels from hydrogen which further increases the demand of H2 by 230 PJ (section 4.3). If DAC is not available at industrial scale, then CO2 emission from biomass could be an alternative source. However, it is also important to ensure sustainability of biomass and minimize its footprint across the entire supply chain (from planting and harvesting tress to shipment/transportation). Current cost of DAC is in the range of USD 100-150/ton CO2 captured[26].

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[25] https://www.iea.org/newsroom/news/2018/may/commentary-offshore-wind-and-hydrogen-for-industry-in-europe.html
[26] https://carbonengineering.com/about-dac/

7. System effects

In this chapter we will consider the demand and supply of hydrogen in the context of the entire energy system of the Netherlands. To study any relevant system effects, we created energy scenarios using the Energy Transition Model (ETM), an online open source energy system simulation model.

The scenarios we created depict one low and one high case for hydrogen demand. They are described below. In Annex G, the links to these online ETM scenarios have been included, as well as a more elaborate description of the scenarios.

7.1 Energy Transition Model and scenarios

This chapters begins with a brief explanation the Energy Transition Model and the purpose of the scenarios we created. This is followed by a brief description of the scenarios themselves.

7.1.1 Introduction to the Energy Transition Model

The ETM[27] was created to allow the exploration of how changes to the energy system impact parameters of interest like CO_2-emissions, energy demand, security of supply, costs, etc. It depicts the entire energy system of a country, including over 50 energy carries and all demand and supply sectors, including international aviation and shipping. It provides immediate feedback of how changes such as an increase of installed offshore wind capacity or of the share of hydrogen-fuelled trucks, for example, affect the rest of the energy system.

As such, the purpose of the ETM is to explore changes at a systemic level, not to model industrial processes in detail, for example. For this project, we wanted to explore how the rest of the energy system impacts the demand or supply of hydrogen and explore any relevant boundaries and limits to the energy system. More information about the ETM can be found in Annex G.

7.1.2 ETM scenarios used for this study

We use the ETM to create and explore two future energy scenarios for 2050 with more than 95% reduction of CO_2-emissions: one with low and one with high hydrogen demand. Both scenarios have been created with a high security of supply for power and other energy carriers, just as this is available to users today. This means that any hourly mismatches between supply and demand of energy are solved using storage of energy or back-up power plants, for example. Also, all available alternatives to hydrogen, like biomass, electrification, geothermal heat, etc. are taken into account. In fact, we find that in order to maintain a high security of supply, the low hydrogen demand scenario requires a large demand of biomass. The high hydrogen demand scenario in turn does not require a large role for biomass but does not rule it out.

These two scenarios have been created to be broadly consistent with two of the four '*Net voor de Toekomst*' (NvdT or Grid for the future) scenarios[28]: national and international steering (NvdT, 2017).

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[27] https://energytransitionmodel.com/
[28] https://www.netbeheernederland.nl/nieuws/resultaten-onderzoek-net-voor-de-toekomst-1204

This means many assumptions regarding the part of the energy system that is not *directly* related to hydrogen, such as electrification of transport and mobility, how power is supplied, etc. are based on the NvdT scenarios that were created in 2017 and 2018 for Netbeheer Nederland. We base our scenarios 1 and two on the NvdT scenarios as shown in Figure 24. The national steering scenario on which scenario 1 is based, pre-supposes near self-sufficiency of the energy system as far as power and hydrogen are concerned (some other carriers may still be imported). For the international steering scenario, on which scenario 2 is based, no such self-sufficiency was assumed.

These NvdT scenarios contain assumptions about the growth in demand for several sectors, but we have tried to create scenario's that exactly replicate the demands for hydrogen from Chapters 4, 5 and 0 for the low and high demand cases. These numbers are based on the current energy system, and therefore imply no growth or change. We exclude the use of 730 PJ of hydrogen for international shipping and aviation in the ETM scenarios, however. As an approximation, all hydrogen for feedstock is modelled in a single sector (Fertilizer), as other processes are not available yet in the ETM. Moreover, ETM scenario 1 contains some hydrogen demand for back-up of electricity generation, which is not taken into account in chapters 4, 5 and 0. It should be emphasized that the numbers in the ETM scenarios are not forecasts. They merely serve to create two separate scenarios and two distinct energy systems. These energy systems can then be investigated for systemic effects such as those covered in section 0.

Figure 24: Schematic illustration of how the two scenarios explored with the ETM relate to the national and international steering scenarios from Net voor de Toekomst*.*

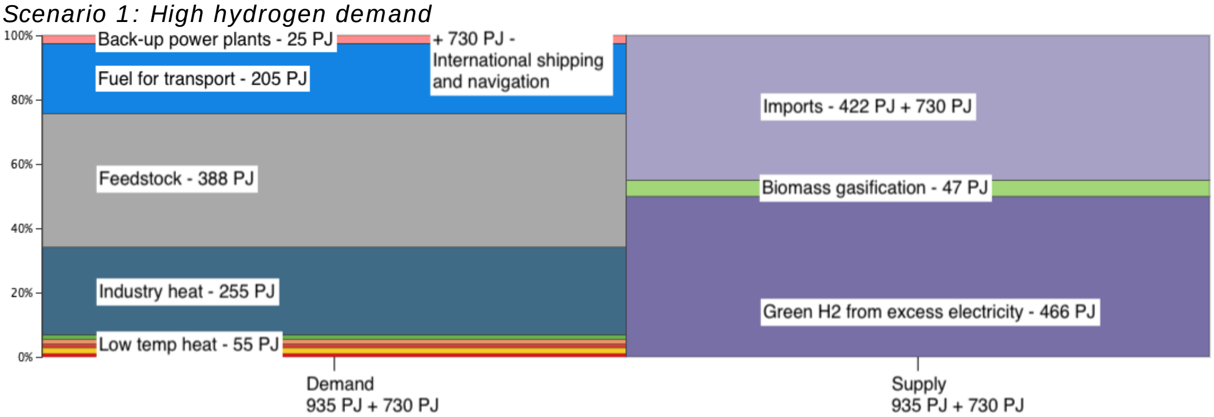
Supply and demand of hydrogen in the ETM scenarios

Domestic supply of hydrogen for ETM scenario 1 is predominantly green hydrogen. The remaining hydrogen demand is met by imports. Domestic supply of hydrogen in ETM scenario 2 is all biomass gasification and the remaining demand is met by imports. We do not make any assumptions on how the imported hydrogen is made as this belongs to the scope of the HyChain2 project. This could even be blue hydrogen or imported natural gas, which is turned into blue hydrogen in the Netherlands. We do not consider blue hydrogen in the context of this study.

This results in the balances for demand and supply hydrogen in scenarios 1 and 2 illustrated in Figure 25 and Figure 26. As is apparent from these figures, demand corresponds to chapters 4, 5 and 0, with some additional hydrogen demand for the back-up of power production.

Table 4 summarizes the installed power production capacities. ETM scenario 1 has a large installed capacity base for renewable electricity production as specified in *Net voor de Toekomst*, and green hydrogen is produced at shore or close to onshore wind or solar sites using power surpluses. There is also still a considerable amount of dispatchable capacity that uses natural gas with CCS, fires solid biomass or green gas. Security of supply is also maintained using hydrogen back-up plants. ETM scenario 2 has some wind and solar, but mainly relies on baseload plants that fire natural gas with CCS, biomass or green gas to guarantee security of supply.

Scenario 1: High hydrogen demand



Scenario 2: Low hydrogen demand

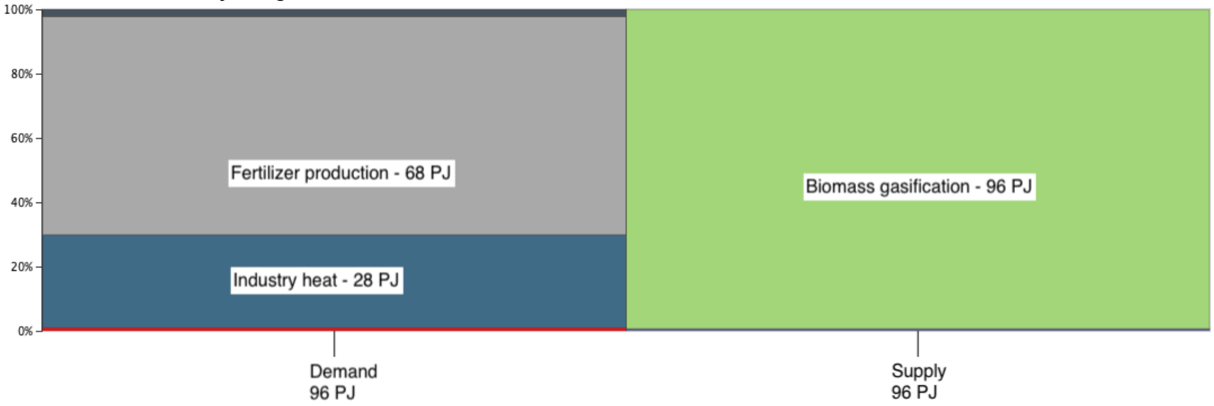


Figure 25 and Figure 26: The balance of demand and supply of hydrogen in ETM scenarios 1 for high and 2 for low hydrogen demand respectively. Note that although the numbers for scenario 1 include the 730 PJ needed for international shipping and navigation, the chart does not.

Table 4 Installed power production capacities for scenarios 1 and 2

Type of power production capacity installed (GWe)	Scenario 1 (high H_2)	Scenario 2 (low H_2)
Solar PV	34	15
Onshore wind	14	5
Offshore wind	53	6
Hydrogen back-up	7.5	-
Other dispatchable capacity (CCS, biomass or green gas)	23	40 [29]

7.2 System effects and boundaries

This section deals with system effects concerning hydrogen demand and supply. When drawing up the ETM scenarios we considered among others the following list of relevant system boundaries or limitations, which all relate to tipping points or alternatives to using climate neutral hydrogen:

- Availability of biomass
- Availability of wind and solar power
- Availability of CCS capacity
- Availability of geothermal energy
- Potential for electrification of energy demand
- Potential for domestic green hydrogen production
- Storage requirements for methane, hydrogen, heat and electricity
- Costs of domestic green hydrogen vs imports

We will not elaborate on all of these in this section. Since we opted to base the scenarios on *Net voor de Toekomst*, quite a few of these boundary conditions had already been set. Instead we will focus on:

- Availability of biomass
- Availability of wind and solar power
- Potential for electrification of energy demand and how this impacts domestic green hydrogen production potential
- (Seasonal) hydrogen storage requirements
- Costs of domestic green hydrogen vs imports

7.2.1 Alternatives to hydrogen

We set out to create scenarios for energy systems with more than 95% reductions in CO_2-emissions. From a systemic perspective, the alternatives to using hydrogen to reduce emissions are green molecules, electricity, heat and CCS. Of these, only molecules provide the advantage of both system-wide applicability and easy (seasonal) storage:

[29] With respect to original the International steering scenario, more biomass and green gas firing capacity was installed to maintain security of supply, since electricity demand is considerably higher in scenario 2. This is because power demand for high-temperature heat is higher (see Chapter 6) than in the original International steering scenario.

- **Electrification** has great potential, but requires molecules for seasonal storage, feedstock and (long distance) transportation
- Residual, geothermal, ambient or surface water **heat** ultimately has limited potential due to temperature level and required proximity to clusters of demand
- Post-combustion **CCS** has capture rates below 100%, limiting its applicability. Pre-combustion CCS (decarbonizing natural gas) is just a means of producing hydrogen

We therefore assumed that molecules will play an important role in any future energy system and also in ETM scenarios 1 and 2. Since fossil molecules can no longer be used without CCS or in large quantities with post-combustion CCS, the only obvious alternative to hydrogen is biomass. Whether or not biomass is a realistic alternative depends on its expected availability for the Dutch energy system.

7.2.2 Availability of biomass

One system boundary to consider therefore is the availability of biomass. *Planbureau voor de Leefomgeving* (PBL) has published some numbers estimating what part of global biomass production might be allocated to the Netherlands[30]. According to PBL, depending on how you allocate biomass potential to the Netherlands anywhere between 300 and 2,400 PJ of biomass[31] may be available. This depends on whether you allocate according to the Dutch share of global population or according to income. The high end of this large range is likely to come down in the future, as global incomes are expected to converge with economic development. Nonetheless, from this large range we concluded a bio-based energy system *could* be an alternative to one based on hydrogen. ETM scenario 2 is therefore mostly based on biomass and uses ~1,400 PJ of biomass carriers excluding any used to replace fossil-based international marine bunkers or aviation fuels. In scenario 2, we also take the potential of the alternatives like geothermal, CCS etc. into account. For this reason, the 2,400 PJ potential is not needed. The total costs associated with this scenario are sensitive to the uncertain future price of biomass.

Of course, whether biomass will *actually* turn out to be the preferred alternative depends on its relative pricing during the transition period, for instance, and its acceptance as an alternative. The immense claim on land that production on any significant scale would entail is also a relevant factor. Since biomass has been in use as an alternative green energy source for longer than hydrogen, there is more experience with its implementation. This means there is a possibility that pressure to reduce CO_2-emissions quickly will result in a partial lock-in of biomass use. Bio-based assets acquired to meet 2030 emission targets may well still be around in 2050. It was not the purpose of this project to explore the likelihood of biomass being the best alternative for a CO_2-free future energy system. For the purpose of this project, however, it is relevant to point out the risk of lock-in. More detailed modelling of the entire transition pathway towards 2050 may help to avoid undesirable lock-in of a specific technology. Such a modelling exercise, however, is not part of this study.

[30] https://themasites.pbl.nl/biomassa/
[31] This pre-supposes scientific breakthroughs and increased agricultural yields. It is unclear whether these numbers include 3rd generation biofuels. The land claim associated with these amounts is roughly 16,500 – 133,000 km^2. The land surface area of the Netherlands is 33,893 km^2.

7.2.3 Availability of wind and solar power

A second system boundary to consider is the domestic availability of wind and solar power. We opted for the installed capacities as outlined in

Table 4, which are based on the *Net voor de Toekomst* scenarios for National and International steering. Scenario 1 has a considerably higher installed capacity for solar and wind power than scenario 2, much of which is used to produce green hydrogen. The installed onshore and offshore wind capacities are close to their maximum potentials. PBL estimates the potential for offshore wind capacity to be 60 GW (PBL, 2018). It is hard to imagine political backing for more than 14 GW of onshore wind. The installed capacity of 34 GW of solar PV is smaller than for the Regional steering *Net voor de Toekomst* scenario (84 GW) and could be increased considerably if needed. Scenario 1 nonetheless represents the high end of domestic wind and solar power production.

As is becoming evident already today, in order to realise such large installed capacities of offshore wind and solar PV, more electricity demand will be necessary. The business case for investors benefits from security of demand, after all. Both electrification of the energy system – in particular of industry – and significant amounts of power-to-gas capacity can guarantee such security of demand. It is clear therefore that large capacities of offshore wind and solar PV, further electrification and green hydrogen production are somehow interdependent on each other.

7.2.4 Potential for electrification

Large amounts of wind and solar energy are required to produce large amounts of green hydrogen. Electrification directly impacts domestic green hydrogen production potential, as it competes for the same renewable power supply. We will consider this system effect below.

To what extent can the system electrify?

In scenario 1, most power is produced using wind and solar (see Figure 27). Some dispatchable plants are required using CCS, biomass or green gas and *back-up* power from hydrogen. In a system based on green hydrogen, it makes little sense to have hydrogen power plants run as baseload plants, as this would create a wasteful loop. We expect any scenario containing a high percentage of volatile renewable power, green H2 production and back-up from hydrogen power plants, to be sensitive to the extent of electrification and growth of electricity demand. Hydrogen turbines are flexible but rather inefficient (~34%), which is not an issue if they only run for 300-500 full-load hours. Once their full-load hours increase, however, hydrogen demand rapidly goes up. At the point where hydrogen turbines no longer serve as flexible back-up power but start to run ever more full-load hours, any system based partly on domestic green hydrogen production starts to make less sense. The inefficient cycle of power-to-hydrogen and hydrogen-to-power that is created then becomes too large to ignore. A system optimized to use hydrogen for back-up is different from one that uses hydrogen as just another fuel for electricity production. Large-scale domestic green hydrogen production more naturally fits into the former than into the latter.

Of course, it is hard to predict the extent of electrification and growth of electricity demand. For an energy system described by scenario 1, we tried to determine how far electrification can increase before the hydrogen demand starts to increase rapidly. If we keep the renewable power generation capacity fixed, one could argue that the maximum potential for electrification has been reached at the point where electricity demand increases cause hydrogen back-up plants to be called upon too often. For the purposes of our systemic analysis, we arbitrarily take this to mean an increase of their number of full-load hours from 300-500 to more than 1,500 FLH.

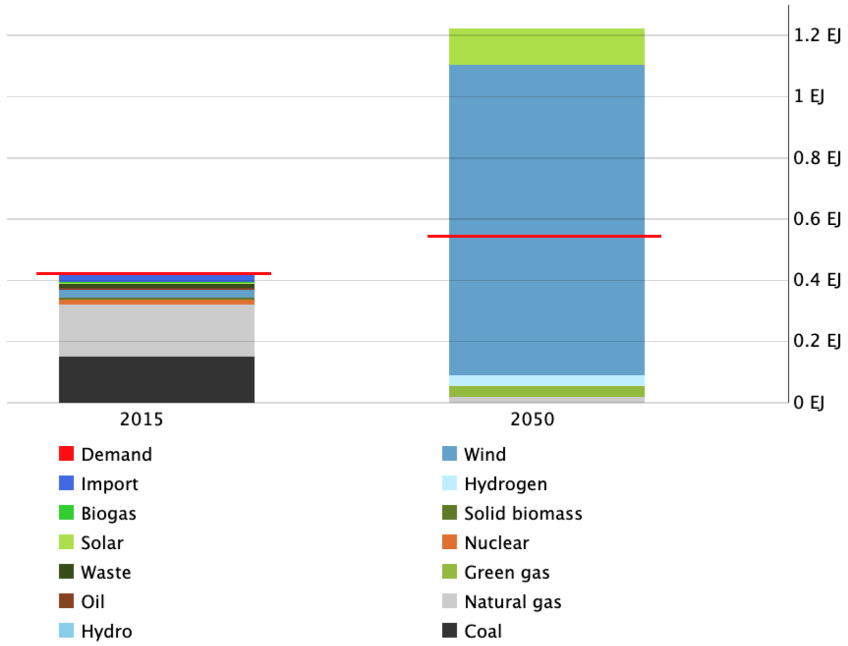


Figure 27: The production of power in 2015 and 2050 in the high hydrogen demand scenario

Using this metric, we can determine that for scenario 1 an increase of power demand from a baseline in 2050 of ~550 PJ to ~810 PJ causes back-up plants to run more than 1,500 FLH. In the base case, ~16% of 550 PJ is met by dispatchable plants (mostly green gas and natural gas with CCS, 1.5% is met by hydrogen back-up plants). In the case of increased power demand, ~24% is met by dispatchable plants (of which 7% is met by hydrogen back-up plants).

To put this into perspective, this increase in demand corresponds to an average annual growth of power demand by ~2% from current levels until 2050. In order to offset this growth in power demand, one could increase the installed offshore wind capacity to 60 GW and solar PV to 84 GW (see 7.2.3). This does little to increase security of supply, however, and just generates more electricity surpluses. In reality, the market may respond by putting a range of solutions in place, such as increasing the available battery capacity (making sure these are connected at the right locations in the grid), increasing the capacity of back-up plants using fuels other than green hydrogen or increasing interconnectivity and relying on neighbouring countries to stabilize the system. More efficient CCGT of even fuel cell power plants that run on green hydrogen would allow for more electricity demand growth, but the same principle applies. Such plants are better suited to running several thousand full-load hours than to running as back-up.

Although the best way to tackle this sensitivity warrants further research, it is clear that the use of hydrogen plants as back-up for large amounts of volatile renewable power production, is vulnerable to growth in electricity demand beyond certain critical levels. This is especially true for years with low wind conditions. At the same time such growth is both desirable and to be expected in a system relying mostly on volatile renewable power sources.

How does electrification influence the potential for green hydrogen production?

In ETM scenario 1, the total demand for hydrogen including international marine bunkers and aviation fuels is equal to ~1660 PJ. Green hydrogen is produced from ~190 TWh (~700 PJ) of surplus electricity from wind and solar. The amount produced is ~470 PJ of green hydrogen using ~75 GW of electrolyser capacity. Back-up power plants use about 25 PJ, so there is 445 PJ available to the remaining end-use sectors. Increasing electrification as described above and prioritizing power-to-heat for industry over power-to-hydrogen, diminishes the production of green hydrogen to ~360 PJ, and increases demand for back-up plants to 170 PJ. This leaves ~190 PJ of domestic green hydrogen to satisfy domestic demand. Imports will have to make up the rest (see Figure 25 and Figure 26).

7.2.5 Hydrogen storage requirements

The seasonal storage requirements for hydrogen in scenario 1 is ~50 PJ (~14 TWh) as shown in Figure 28. The Netherlands currently has ~470 PJ (~130 TWh) of natural gas storage capacity, but this is mostly based on depleted gas fields. According to recent research by TNO, enough storage capacity for hydrogen in salt caverns can be created in 2050 to meet seasonal fluctuations in national demand (TNO, 2018, p. 56). In fact, the availability of sufficient gas storage is an opportunity for a hydrogen-based economy.

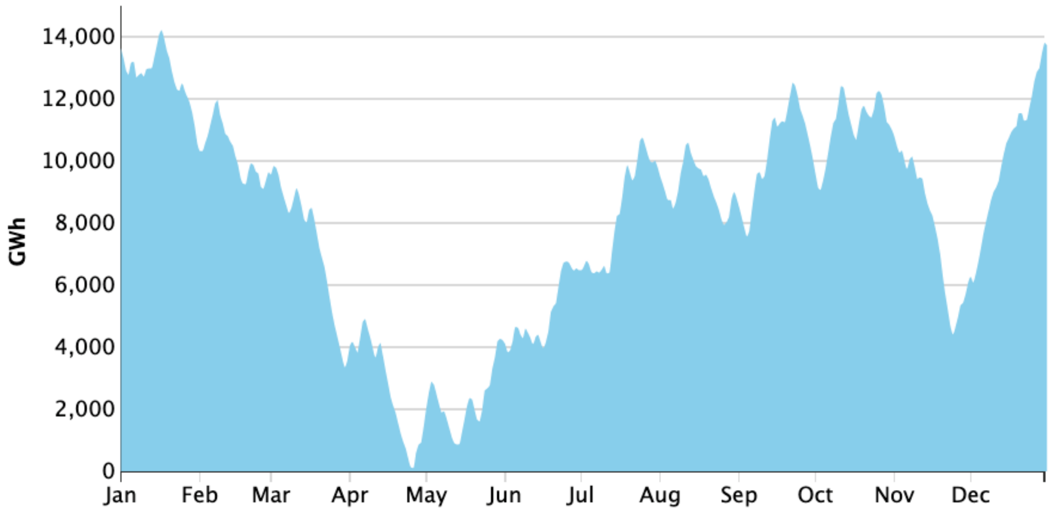


Figure 28: Hydrogen storage throughput the year in the high hydrogen demand scenario. 1 TWh = 3.6 PJ, so 14 TWh = 50.4 PJ

7.2.6 Costs of domestic green hydrogen vs imports

According to the sensitivity analysis done by Kalavasta in HyChain2, the range of *lowest* potential costs for imported hydrogen varies between 1.6 and 2.3 €/kg (i.e. 13.3 – 19.2 €/GJ) (HyChain II, 2019). This lower range mostly corresponds to hydrogen from within Europe and it is not certain that these countries of origin will have a large export potential. The total range of potential hydrogen import costs listed by Kalavasta is much larger. The green hydrogen production in ETM scenario 1 is assumed to cost anywhere between 1.2 €/kg and 3.2 €/kg (9.9 – 26.7 €/GJ) depending on the costs charged for surplus power (no negative prices are assumed). The costs of €3.2 €/kg for hydrogen produced offshore and piped to shore are in line with the assumptions Kalavasta makes for Dutch hydrogen production costs in its report for HyChain2. Needless to say, these costs are very sensitive to the costs of offshore wind power and electrolysers, which were already mentioned as tipping points in Chapter 6.2. We do not explore whether hydrogen will be produced cheaper thanks to discounted power prices, but base domestic hydrogen production costs on assumptions made in the *Net voor de Toekomst* publication.

As we saw in 7.1.2, should hydrogen become a major part of the energy system, the Netherlands is likely to require significant import capacity for hydrogen. Considering the limited domestic potential for producing green hydrogen, importing a little more would not be too difficult, especially if imported hydrogen turns out to be considerably cheaper than domestically produced green hydrogen. Without the use of large installed capacities of domestic power-to-gas to stabilize the grid and provide security of demand, however, investments in large scale offshore wind would be harder to finance. It is also questionable whether large installed capacities of solar and wind power can be integrated into the energy system, unless huge strides are made in direct electricity storage. Without the availability of massive amounts of offshore wind, the goal of reducing CO_2-emissions by more than 95% becomes harder to achieve, except by importing even more hydrogen or large amounts of biomass.

We recommend further research into the export potential of countries that fall in the lower range of hydrogen import costs for the Netherlands cited by Kalavasta. If this turns out to be large enough, imported hydrogen could stymie investments in domestic green hydrogen production and indirectly weaken the business case and rationale for large scale offshore wind production.

It stands to reason that bringing down the costs of domestic green hydrogen production should be a core task of any Dutch government planning to tackle climate change. As wind offshore wind costs before, this will largely come down to an active government intervention by enabling markets.

7.3 Regionalization and cluster effects

The demand in ETM scenario 1 as well as the required supply of hydrogen will not be spread equally and uniformly over the Netherlands. Appropriate infrastructure needs to be in place to transport, distribute and store the hydrogen or hydrogen-based energy carriers. This section provides a first insight in the clustering of hydrogen demand based on the scenarios described above. In addition, we elaborate on the effect of taking into account international marine and aviation bunkers as well as the export of energy carriers and molecules to the *Hinterland*.

7.3.1 Methodology

The analysis described in this section is based on a method developed by the *Werkgroep Waterstof* within the context of the Dutch Climate Agreement negotiations (Werkgroep Waterstof - Klimaataakkoord, 2018). This method aims at determining the demand and supply of hydrogen in the twelve provinces and five main industrial clusters within the Netherlands. Gasunie has used this information to determine the requirements for a future hydrogen infrastructure. Within this report we will only focus on the demand of hydrogen, but we will extend the analysis to include international marine and aviation bunkers as well as the export of energy carriers from the Netherlands to the *Hinterland*.

Scenario 1: high hydrogen demand

In ETM scenario 1 described above a demand for hydrogen of ~1650 PJ was used. We used the Gasunie method to determine the regional distribution of this demand. Gasunie uses the following rules to determine the hydrogen demand in the various regions and industrial clusters from the total expected demand of hydrogen for specific applications:

- Built environment:
  - Pro rata of the number of inhabitants per province
- Mobility:
  - Pro rata of the number of inhabitants per province
- Electricity production:
  - Groningen Seaport area: 50%
  - Port of Rotterdam area: 50%
- Industry feedstock (following the present distribution):
  - Zeeuws-Vlaanderen: 37%
  - Port of Rotterdam area: 22%
  - South Limburg: 18%
  - Groningen Seaport area: 13%
  - Port of Amsterdam - IJmuiden: 10%
- Industry -heat (following Blueterra study):
  - Port of Rotterdam area: 48%
  - Zeeuws-Vlaanderen: 26%
  - South Limburg: 15%
  - Port of Amsterdam - IJmuiden: 10%
  - Groningen Seaport area: 1%
- Agriculture:
  - Port of Rotterdam area (“Westland”): 100%

We have extended this analysis for the demand of international marine and aviation bunkers and the transit of energy carriers through the Netherlands. For those energy flows we have assumed the following distribution:

- International marine bunkers (based on fuel sales):
  - Port of Rotterdam area: 70%
  - Port of Amsterdam - IJmuiden: 30%
- International aviation bunkers (based on public statements about kerosene delivery to Schiphol airport):
  - Port of Rotterdam area 50%
  - Port of Amsterdam - IJmuiden: 50%
- Export of liquid energy carriers (based on annual tonnage of cargo):
  - Port of Rotterdam area: 85%
  - Port of Amsterdam - IJmuiden: 15%
- Export of gaseous energy carriers (only Groningen Seaport area has a large-capacity natural gas infrastructure to the Hinterland):
  - Groningen Seaport area 100%

Scenario 2: Low hydrogen demand

ETM scenario 2 projects that hydrogen will only be used as feedstock in the fertilizer industry and as fuel for high temperature heat in the petrochemical industry. We will therefore use a much-simplified version of the Gasunie method in which we have assumed that:

- Industry feedstock (following the current geographical distribution of fertilizer production capacity):
  - Zeeuws-Vlaanderen: 60%
  - South Limburg: 40%
- Industry -heat (identical to the high case scenario):
  - Port of Rotterdam area: 48%
  - Zeeuws-Vlaanderen: 26%
  - South Limburg: 15%
  - Port of Amsterdam - IJmuiden: 10%
  - Groningen Seaport area: 1%

7.3.2 Cluster effects of domestic hydrogen demand

Based on the demands for hydrogen in the high case and low case scenarios described in section 7.1.2 we have determined the domestic demands for hydrogen per sector and or application.

Table 5: Domestic demand of hydrogen per sector/application for the high case and low case scenarios described above.

Sector/application	Scenario 1 High hydrogen demand (PJ)	Scenario 2 Low hydrogen demand (PJ)
Built environment	55	0
Mobility	205	0
Electricity production	25	0
Industry – feedstock	388	68
Industry – heat	255	28
Agriculture	14	0
Total	**942**	**96**

In order to get an insight in the geographical distribution of the domestic hydrogen demand, the analysis described in the previous chapter has been applied to the data from Table 5. The results are displayed in Figure 29.

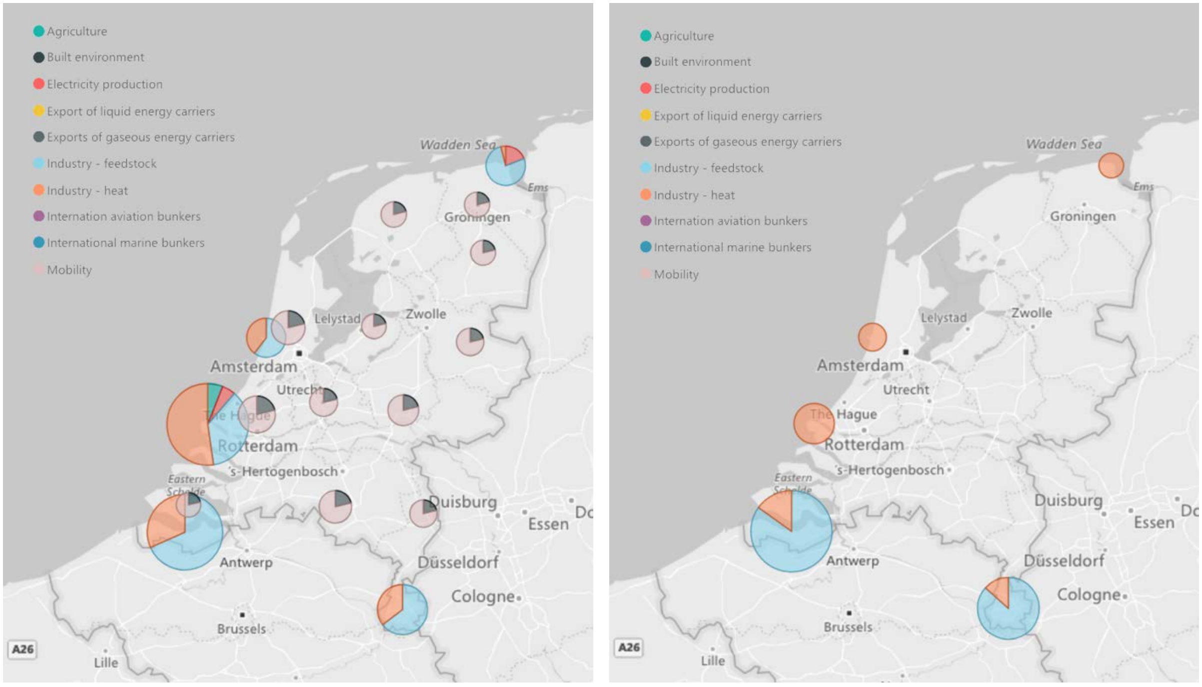


Figure 29: Domestic demand of hydrogen per cluster and province and per sector and application for ETM scenario 1 (left) and ETM scenario 2 (right). The relative size of the pie charts is consistent within each scenario, but not between the two scenarios. For the data underlying these charts see Table 5.

7.3.3 International marine and aviation bunkers hydrogen demand

As stated in Chapter 5, bunker fuels will most likely be replaced by hydrogen or synthetic fuels. This adds a significant amount of hydrogen demand to the Dutch energy system. As we have not looked in detail into the future demand of bunker fuels within this study, we have assumed present levels of demand. Table 6 shows the hydrogen demand for both sectors.

Table 6: Hydrogen demand for international marine and aviation bunkers. We have assumed present levels of demand and used those for both scenarios 1 and 2.

Sector/application	Scenario 1 High hydrogen demand (PJ)	Scenario 2 Low hydrogen demand (PJ)
International marine bunkers	500	0
International aviation bunkers	230	0

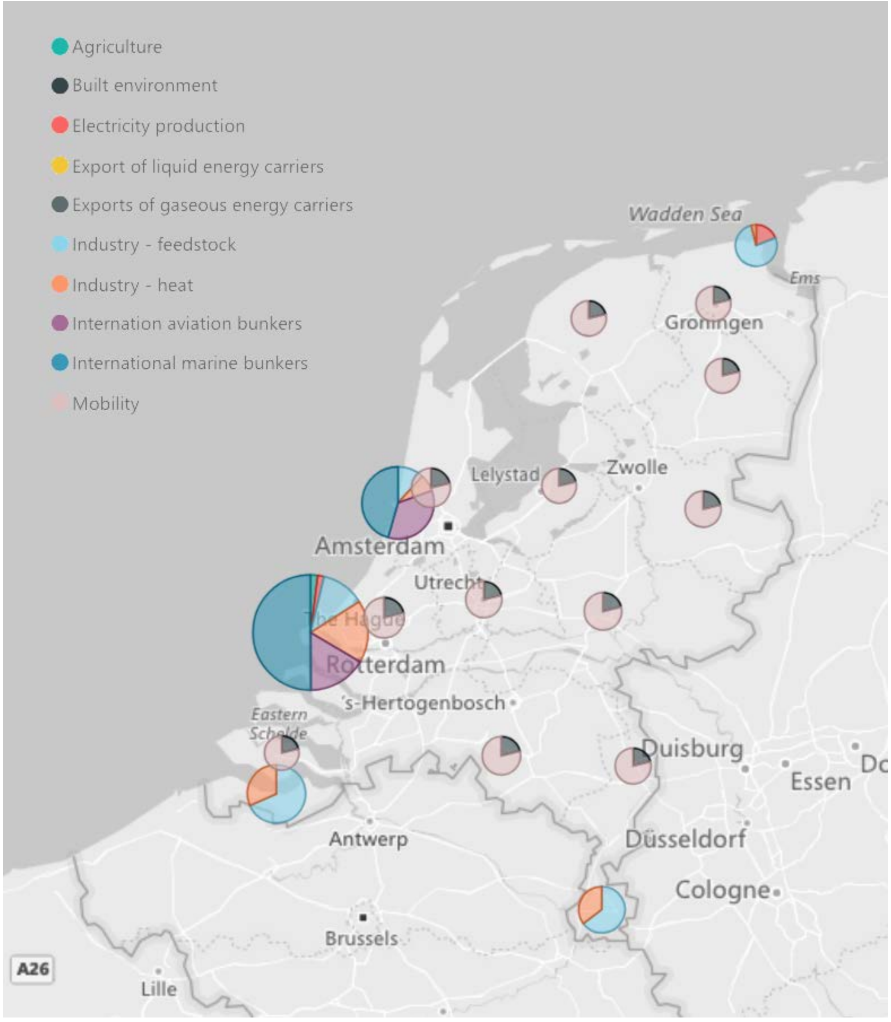


Figure 30: Domestic demand of hydrogen per cluster and province and per sector and application for ETM scenario 1 including the demand for international marine and aviation bunkers. Scenario 2 is unaffected by these sectors.

Again, we used the method described above to determine the geographical distribution of these demands. Figure 30 shows a graphical representation of this geographical distribution.

7.3.4 Export of energy carriers to the *Hinterland*

The Netherlands, in particular the Ports of Rotterdam and Amsterdam, serve an important function in the transit of energy carriers to the Hinterland. Fossil energy carriers currently make up a significant part of the export from the Netherlands. Leaving aside natural gas exports, over 6,500 PJ of oil and oil products and over 1,100 PJ of coal pass through the Netherlands. In a decarbonized future, these fossil carriers will have to be replaced. In order to get a feeling for the impact this will have on the future hydrogen demand in the Netherlands, we have added these carriers to our analysis. We have assumed present levels of demand for export from the IEA energy balance for 2017 and have made an assumption on which of these carriers could be replaced by gaseous hydrogen directly or by liquid synthetic carriers based on hydrogen. Table 7 shows the hydrogen demand for both sectors. In Scenario 2 only biomass will be exported. The results presented in this subsection represent first estimates that need further research to be refined. Also, the export of gaseous energy carriers will face competition from supply from other countries through existing gas infrastructure, in particular from the South of Europe or Northern Germany.

Table 7: Hydrogen demand for the export of energy carriers to the Hinterland. We have assumed present levels of demand and used those for both the high case and low case scenarios.

Sector/application	Scenario 1 High hydrogen demand (PJ)	Scenario 2 Low hydrogen demand (PJ)
Export of liquid energy carriers	2,561	0
Export of gaseous energy carriers	2,204	0

Again, we used the method described above to determine the geographical distribution of these demands. Figure 31 shows a graphical representation of this geographical distribution.

7.3.5 Key findings on infrastructure consequences and cluster effects

In ETM scenario 1, hydrogen will make its way into most parts of the Dutch energy system. Industry and centralized electricity production will make up a significant part of this demand (~70%). This industrial demand is clustered in the five main industrial clusters in the Netherlands, making these clusters the ideal nucleation point for a hydrogen-based energy system. The decentralized hydrogen demand for the built environment and mobility can benefit from the large infrastructure needed for the industrial demand.

The aforementioned effect becomes even stronger when the demand for international marine and aviation bunkers are taken into account. In the high case scenario this demands is met by hydrogen-based synthetic fuels. Bunker fuels are now mainly supplied through the Port of Rotterdam and the Port of Amsterdam. This suggests that the hydrogen demand in the Port of Rotterdam and Port of Amsterdam regions will increase even more. That is, assuming that current refining capacity is eventually replaced by the production of synthetic fuels. The latter may also shift to countries with abundant availability of cheap hydrogen and green carbon.

If we also take the transhipment of energy carriers through the Dutch ports into account, the domestic demand gets overshadowed by these demands. In the high case scenario these carriers will be replaced by gaseous hydrogen directly or by hydrogen-based synthetic carriers. As the demands for these exported carriers are much higher than the domestic demands, the Dutch energy system will most likely adapt to the energy system of the surrounding countries. In other words, it is important to keep an eye on the developments in these countries, in particular Germany. A Dutch energy system like described by scenario 2 (low hydrogen demand) cannot be combined with a similar role for Dutch industry and ports, if Germany has a system that looks more like scenario 1 (high hydrogen demand).

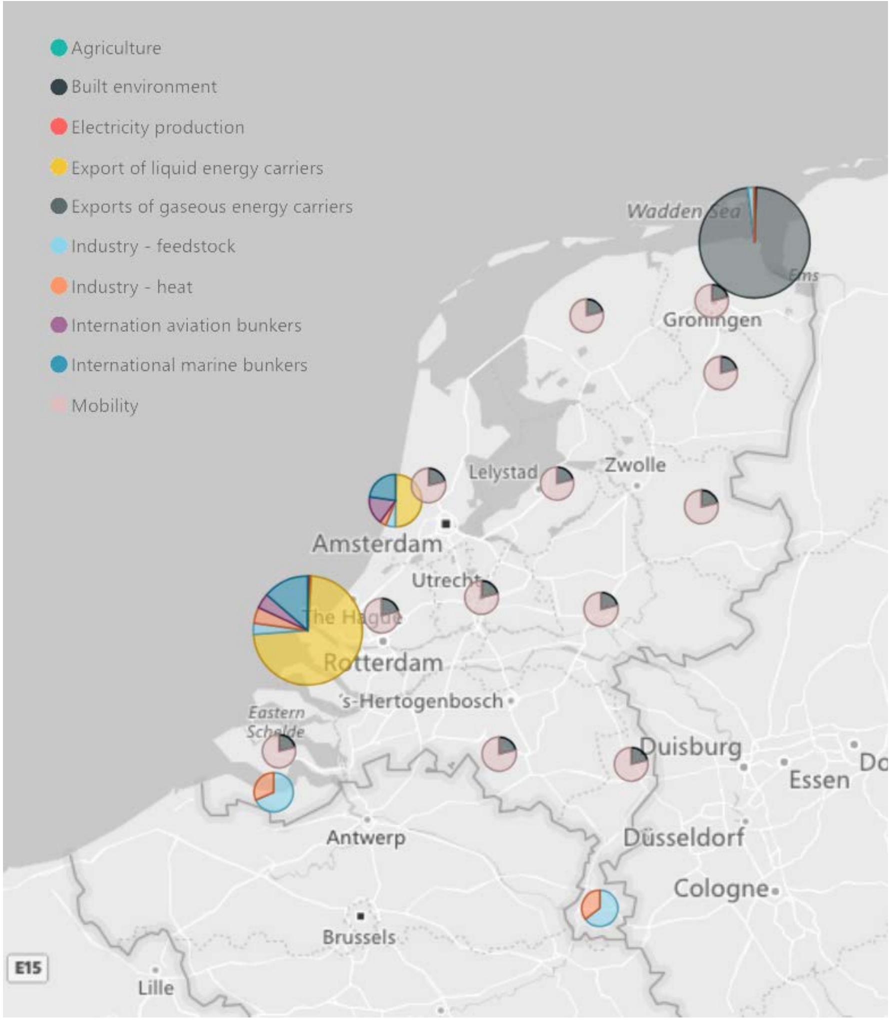


Figure 31: Domestic demand of hydrogen per cluster and province and per sector and application for the high case scenario including the demand for international marine and aviation bunkers and the export of energy carriers to the Hinterland, both gaseous and liquid. The low case scenario is unaffected by these sectors.

Finally, a shift from solid and liquid energy carriers to gaseous hydrogen means that the Dutch exports will face competition from other countries that have a direct gas infrastructure to our surrounding countries, in particular competition from Southern European countries. This makes the demand for export energy carriers more uncertain and this effect should be studied further in a follow-up project.

8. Conclusions and recommendations

Several factors play a key role in the development of hydrogen market. A few technical as well as sector specific developments are necessary. However, the developments are also intensively dependent on political framework as well as macro-economic policies.

8.1 Literature review

From the most recent literature review, we observed a growing projected use of hydrogen in the future energy system. The range is broad (0 – 1900 PJ/yr) because the assumptions and applications in the reported studies varied significantly. Although uncertain, a possible role for hydrogen exists in each of the end-use sectors. The use of hydrogen, as fuel for energy and as feedstock for chemical reactions, leads to a high level of complexity and many competitive pathways. Integral assessments with optimization and simulation models which have carefully integrated all relevant factors in their system are desired to obtain a better understanding of the future role of hydrogen in our society.

8.2 Most influential tipping points

From the literature review and the demand analysis (including IN2050 modelling), we found a huge difference between, low and high hydrogen demand scenarios. For various applications, an alternative to hydrogen is possible. The application of hydrogen as feedstock and in mobility sector requires large adjustments in the entire supply chain to change towards a hydrogen-based process. Nonetheless, we have found the following major tipping points which will influence the future possible routes in various sectors:

Economical

- Availability and costs of offshore wind (640 PJ)

  If the Netherlands favors competitive renewable electricity prices, the production and use of green hydrogen are likely to rapidly take off. For investments in "green" production routes, the Netherlands could be a competitive location.

- Availability and price of biomass (1100 PJ)

  Biomass is a possible yet competitive alternative in various applications, specifically in energy and feedstock. Estimations about the availability and thus, price of biomass show a large uncertainty. If only minimal biomass turns out to be sustainably available, hydrogen is one of the few options left. Therefore, this has a very large influence on the final hydrogen demand.

- Performance of electrical storage

  This will be of influence for applications which have an electric alternative. Storage price will be a significant parameter which could impact the stability of the electricity price, which is of utmost importance for continuous processes. Further, the performance in terms of weight and size is of influence for the use of electricity in the mobility sector.

Social and political

- The availability but more important, acceptance of CCS (890 PJ)

  When CCS is accepted and ready for implementation, large-scale production of blue hydrogen can potentially take place. This will boost the scale of market update and develop optimum price level to initiate rapid development in hydrogen economy. Further, this could favor hydrogen-based investment over biomass counterparts. Thereby, on the long run this tipping point can significant decide the size of the future hydrogen demand. System of certifications of origins can be created to facilitate the use of blue hydrogen which is accepted by the government, NGOs and end users.

- Safety perception of hydrogen

  Especially for hydrogen in the built environment but also in mobility, the safety aspects play a dominant role. This will decide the acceptance of hydrogen technology but might also result in regulations which make the application more expensive. Possible early application of hydrogen in mobility sector could lead to early societal acceptance.

- Government stimulation of green energy and hydrogen

  The availability of offshore wind is an enabler for green hydrogen production. And green hydrogen production is an enabler for offshore wind because it can prevent electrical congestion and balance issues. When both are stimulated by government, local supply of green hydrogen is created which will stimulate hydrogen use on the demand side. In the long term, a trading facility for hydrogen market would stimulate an efficient as well as large scale hydrogen economy.

8.3 System effects

- **Concerted action is needed**

  The identified tipping points are key to bridging the gap between incremental/organic change towards a hydrogen economy and the high potential hydrogen demand scenarios. Concerted action and policies are required to influence these in the desired direction. This may require an active choice rather than just leaving it to the market to decide.

- **The competitiveness of domestic green hydrogen matters**

  The competitiveness of domestic green hydrogen production will not just determine how much hydrogen is imported, but it is also likely to be an important factor in the integration of large quantities of offshore wind into the energy system. As such, it will influence how easy a 95% CO_2-emissions reduction pathway is likely to be.

- **It takes molecules, but which ones?**

  The systemic role molecules play in stabilizing and increasing security of supply suggests that biomass and hydrogen (or related carriers) will play an important role in the future. Which of these will be most prominent is hard to predict, but a partial lock-in of biomass is possible, if policies mostly focus on short-term reductions of CO_2-emissions.

- **Green hydrogen, electrification and renewable electricity potential are interconnected**

  Potential for domestic renewable power and therefore, green hydrogen production is significant, but any scenario with significant hydrogen demand will rely on considerable amounts of imported hydrogen. Domestic production potential of green hydrogen depends on the extent of electrification. Since, electrification is also a pre-condition for a large installed renewable power generating capacity, and the tipping points identified in part also affect the attractiveness of electrification, this warrants further research. Should North Sea countries integrate their exploitation of offshore wind resources, this would be a boon.

- **What neighboring countries do, matters**

  When considering future flows of hydrogen between centers of demand and supply it is important to also look at the potential throughput of energy carriers and molecules to the Hinterland.
  Keeping an eye on developments in Germany and other main recipients of exported energy carriers and molecules from the Netherlands is necessary. A low hydrogen demand energy system in the Netherlands would not fit well into a NW Europe that is mostly hydrogen-based and vice-versa. Dutch industry and ports would stand to lose international market share. In addition, technology choices on a global and European level will significantly affect expected cost reductions for these technologies.

- **The Netherlands are well-positioned for a hydrogen economy**

  The geography, the nature of the Dutch energy system and the role Dutch ports and industry play in supplying molecules and energy to the Hinterland make it extremely well suited to the shift towards a hydrogen-based economy.

9. References

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Werkgroep H2, 2018 Waterstof vraag en aanbod nu – 2030 – 2050; behoefte aan waterstof infrastructuur

Annex A RVO reporting requirements

a. The next steps the consortium will take upon completion of the project to execute and implement in the market what has been researched

After the completion of the first three parts of the Hychain project the further definition of Hychain four will start. In this project many still open questions can be addressed to get a better insight in the full hydrogen chain. For instance the translation from the more abstract and nationwide results to more specific chains which involve specific companies.

b. The expected CO2 reduction that would be achieved upon execution and implementation in the market of what has been researched

The total future hydrogen demand will have a range between 100 PJ (0,8 Mton) and 1600 PJ (13 Mton). Reduced CO_2 emissions can be estimated using the reference of fossil fuel emissions. These can range between a CO_2 emission of 55 kg/GJ for methane and 98 kg/GJ for coal. On average the emission is assumed to be 75 kg/GJ. This gives an estimate for CO_2 reduction from 7.5 Mton to 120 Mton.

c. The financial or economic opportunities, including one or more business cases which are necessary to successfully apply the concept or technology

A large hydrogen economy can be very favourable for the Netherlands. The position close to the North Sea gives possibilities for both import of hydrogen and production using offshore wind. When infrastructure is available not only the Netherlands but also parts of Germany and Belgium can be supplied through the Netherlands.

d. The non-technological factors that could play a role in the application of the concept or technology in the market and the way these factors are dealt with

For non-industrial use the safety perception of hydrogen will be an important factor. Being open and transparent about the risks and solutions will help towards a realistic safety perception. In industry there is already a lot of experience using hydrogen, this can help to implement this technology in a safe way for other sectors.

e. If the project is about technology development; the embedding of this technology in the energy value chain

Not applicable

Institute for Sustainable Process Technology

f. The scalability and repeatability of what has been researched

In this study we considered the Netherlands and zero growth. Both when assuming growth or including surrounding countries the hydrogen demand will increase. The tipping points on the other hand are more general and will hold for other scopes as well. Although a world-wide scale can give rise to new system boundaries and tipping points.

Annex B List of studies

AFHYPAC (2018) Developing Hydrogen for the French Economy, a prospective study, 2018.

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Shell Sky (2018) Sky, Meeting the goals of the Paris Agreement, Shell International B.V. (numbers in associated Excel spreadsheet), Both the global and European (EU) projections are part of our meta-analysis.

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Umweltbundesamt (2014) Benndorf et al., Germany in 2050 – a greenhouse gas-neutral country, April 2014.

Annex C Definitions of hydrogen use

Energetic use of hydrogen

Hydrogen is applied to generate heat or power.

Examples:
- fuel for power plants
- fuel for fuel cell electric vehicles
- fuel for high or low temperature heat (e.g. in the natural gas network).

Non-energetic use of hydrogen

Hydrogen is applied as feedstock for a chemical process. As a result of this chemical conversion process, hydrogen, or part of its energy content, is stored in the product.

Examples:
- for ammonia production (reaction of H_2 with N_2)
- for iron/steel production (reaction of H_2 with iron oxide)
- for carbon-based chemicals production (reaction of H_2 with CO_2, e.g. to produce ethylene, formic acid, or methanol)
- for carbon-based fuels production (reaction of H_2 with CO_2, e.g. to produce methane, diesel or kerosene).

Remark: intermediate storage of hydrogen

To ease transportation of hydrogen, it may be attractive to convert it temporarily into other materials. The market demand for these materials is currently very low and their function is thus only as intermediate storage option for hydrogen.

Examples:
- liquid organic hydrogen carriers
- metal hydrides.

Annex D IN2050 Methodology

The IN2050 model has 2 sub models to forecast scenarios for industrial fuel demand classified in 3 temperature ranges:

- Low temperature: 100-250°C
- Medium temperature: 250- 500°C
- High temperature: >500°C

1. Function model: The model provides an estimation of integrated cost of heat production and margin price for following technologies.

100 - 250°C	250 - 500°C	>500°C
Gas Boiler	Gas Boiler	Gas Furnace
Hydrogen Boiler	Hydrogen Boiler	Gas Furnace
Electric Boiler	Electric Boiler	Electric Furnace
Biomass Boiler	Biomass Boiler	Biomass Furnace
Mechanical Vapour Recompression	Gas Turbine	Hydrogen Furnace
Thermal Vapour Recompression	Steam Turbine	Coal Furnace
Deep Geothermal	Combined Cycle Gas Turbine	Gas Furnace + CCS
Gas Turbine	Coal CHP	Coal Furnace + CCS
Steam Turbine	Biomass CHP	Blast Furnace/Basic Oxygen Furnace
Combined Cycle Gas Turbine	Hydrogen Fuel Cell	Electric Arc Furnace
Coal CHP		
Biomass CHP		
Hydrogen Fuel Cell		

Figure 32: Technologies analysed in IN2050 model for merit order estimation

- **Margin price** is a measure to estimate whether a heat generating installation is profitable or not as compared to assumed price at which heat is sold. The calculation of this margin depends on whether the function is subsidized or not. For installation with subsidies, the margin is evaluated as:

$$\text{Profit Margin} = \text{Subsidy amount} - \text{Levelized cost of heat}$$

For, functions which are not subsidized the profit margin is calculated as:

$$\text{Profit Margin} = \text{Reference price of heat} - \text{Levelized cost of heat}$$

- The **reference price** of heat for that year is defined as the price of heat in that year which is obtained by multiplying the lowest LCOH (levelized cost of heat) in that year with a factor of 1.1.

$$\text{Reference price of heat} = 1.1 * \text{Levelized cost of heat}$$

- The **profit margin** is calculated for each year till 2050 to take into account taxes, indices, inflation rate, CAPEX reduction etc.:

2. Capacity Model: The model estimates current thermal capacity and heat demand, followed by its evolution till 2050.

The first task of the model is to estimate the current heat demand and thermal capacity of the industry sector based on the available data on fuel usage, CHPs installations, efficiency of heating systems, etc.

Thereafter current fossil based capacity is linearly phased out till 2050. Due to decrease in fossil capacity, a capacity gap occurs (difference between existing and needed capacity) which is shown in Figure 33: Capacity gap (Total capacity-existing capacity)

. The gap is filled by CO2 neutral heating systems. The system which has the highest profit margin for that particular year gets 100% share, of the gap. For ex: if in a year electric boiler for MT range is the most profitable, then the capacity gap for MT range during that particular year is entirely filled by electric boiler. This profit margin is obtained from the function model. Further, it is assumed that YoY increase in heat demand negates the YoY increase in energy efficiency, i.e. net increase in heat demand is assumed as zero till 2050.

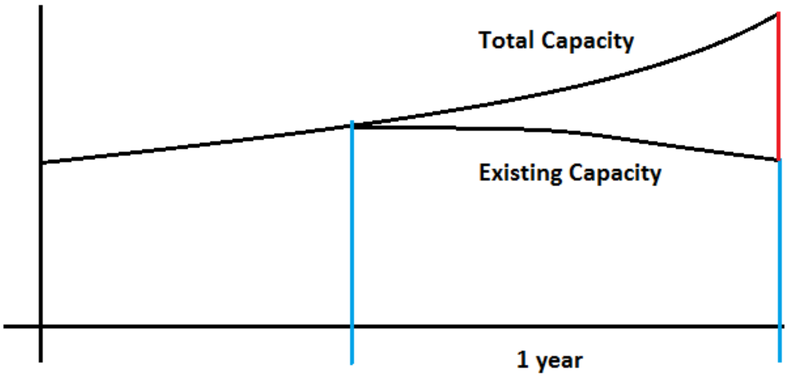


Figure 33: Capacity gap (Total capacity-existing capacity)

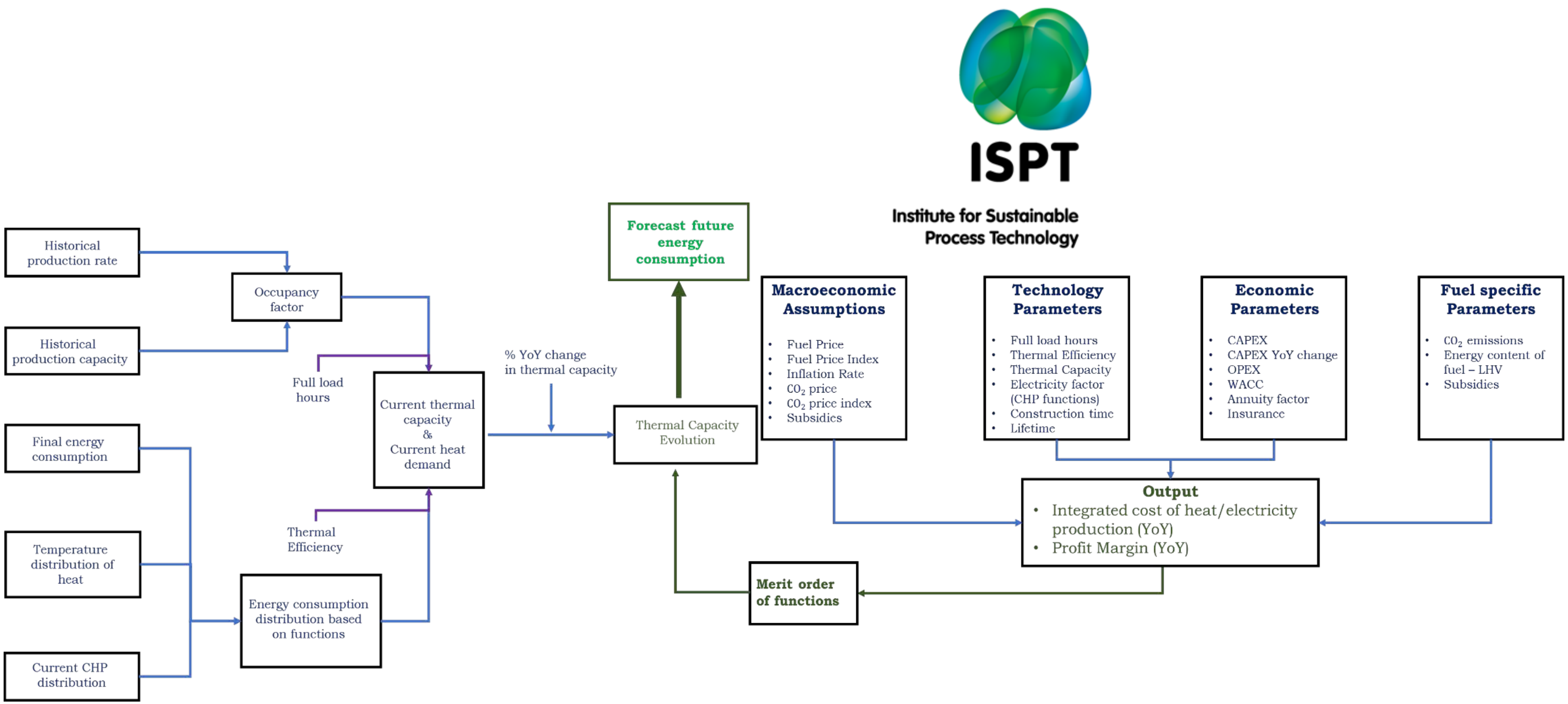


Figure 34: IN2050 methodology (function and capacity model combined)

Using this tooling, the change in energy mix for industrial sector is estimated for the 3 scenarios. In the following section, key findings are presented

Annex E H2 production cost

The estimation on production cost of hydrogen is shown in this annex. Assumed technical and financial parameters are depicted in table below. Further, assumptions on trend as well as cost of fuels (natural gas and electricity) and CO2 are taken from **Error! Reference source not found.**.

The sale price of H2 for possible consumers is assumed as equal to production cost of H2 (neglecting transportation costs). Further, the minimum cost from the Figure 35: Integrated production cost of grey, blue and green H2 is assumed as the price of H2 for that particular year which is provided as an input to the IN2050 model. Thereby, as seen in the figure, the price of H2 follows the trend of blue H2 until 2040, beyond which, green H2 becomes cheaper and its price is used as the assumption.

Table 8: Financial and technical inputs used to estimate production cost of H2

Parameter	Unit	SMR, large scale	SMR+CCS, large scale	PEM
CO2 emission	*ton/MWh Natural gas*	0,20	0,01	0
CAPEX	*Euro/kw*	€ 480,00	€ 1.200,00	€ 1.000,00
CAPEX YoY reduction	*%*	0%	0%	3%
WACC	*%*	8%	8%	8%
Efficiency	*%*	77%	70%	60%
Fixed O&M	*%*	3%	5%	3%
Full load hours	*hrs*	8000,00	8000,00	8000,00

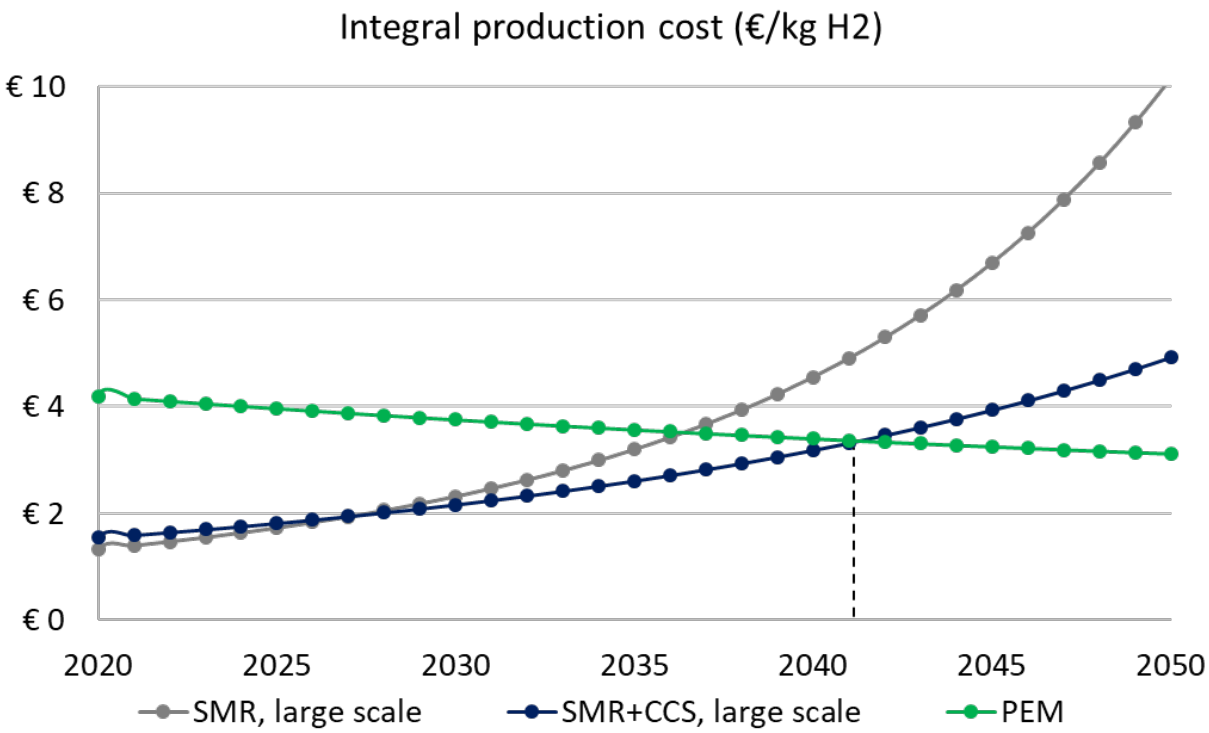


Figure 35: Integrated production cost of grey, blue and green H2

Annex F Fishbones

H_2 demand LT heat

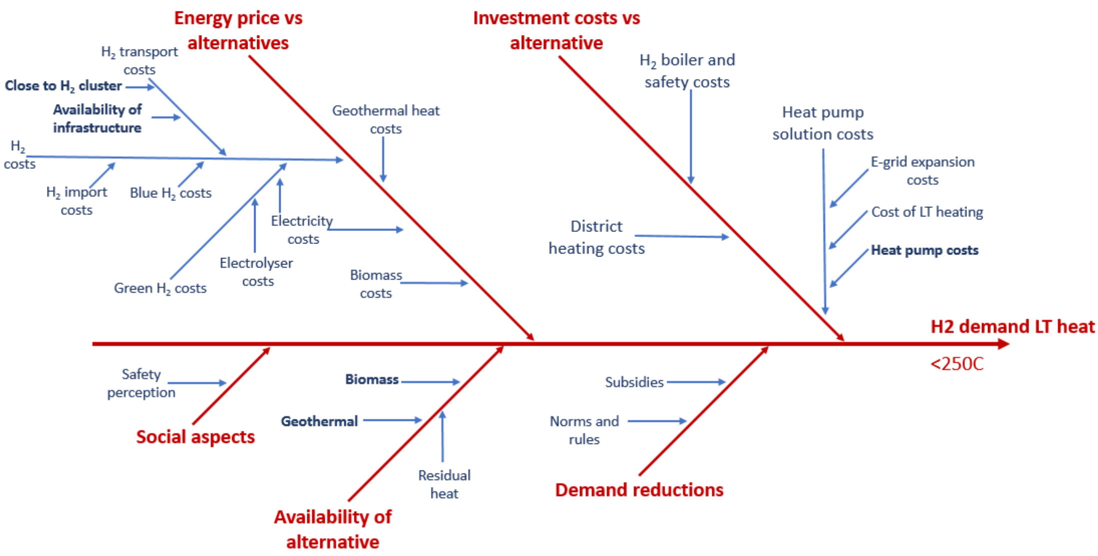


Figure 36: Fishbone LT heat

H_2 demand HT heat

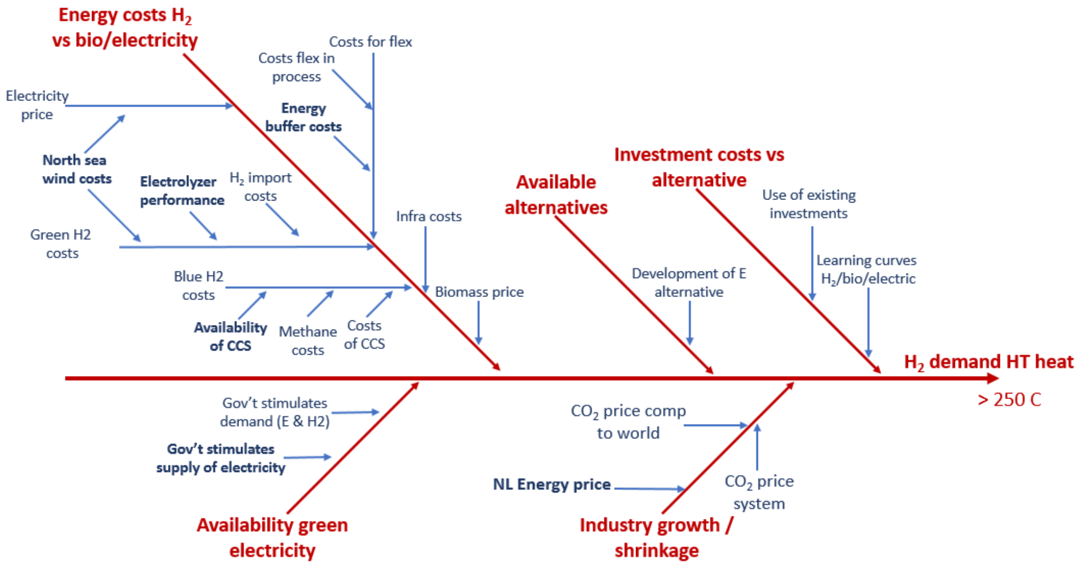


Figure 37: Fishbone HT heat

H_2 demand feedstock

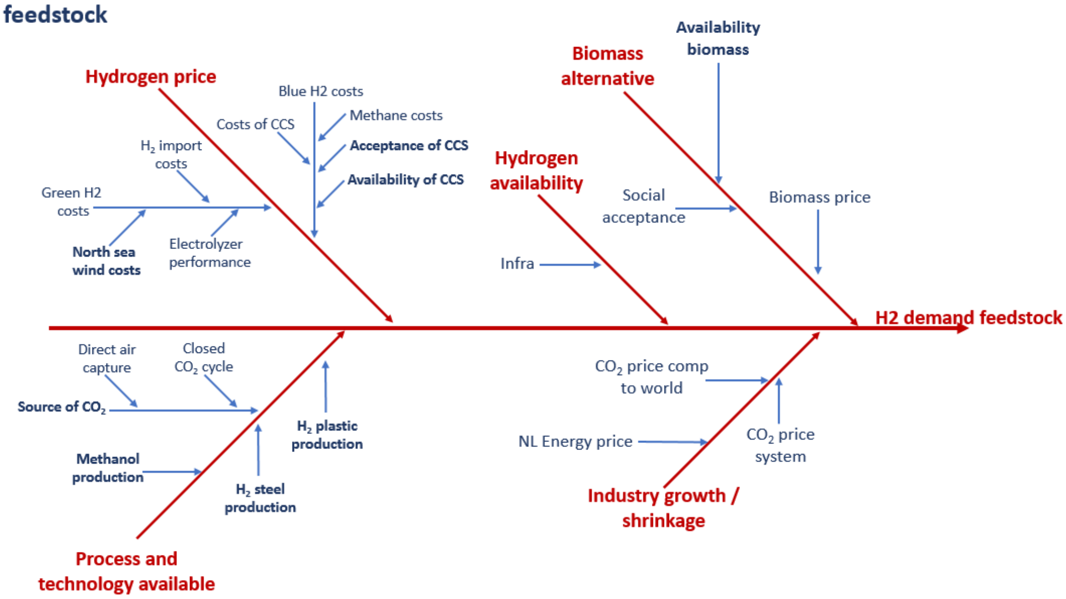


Figure 38: Fishbone feedstock

H_2 demand mobility and transport

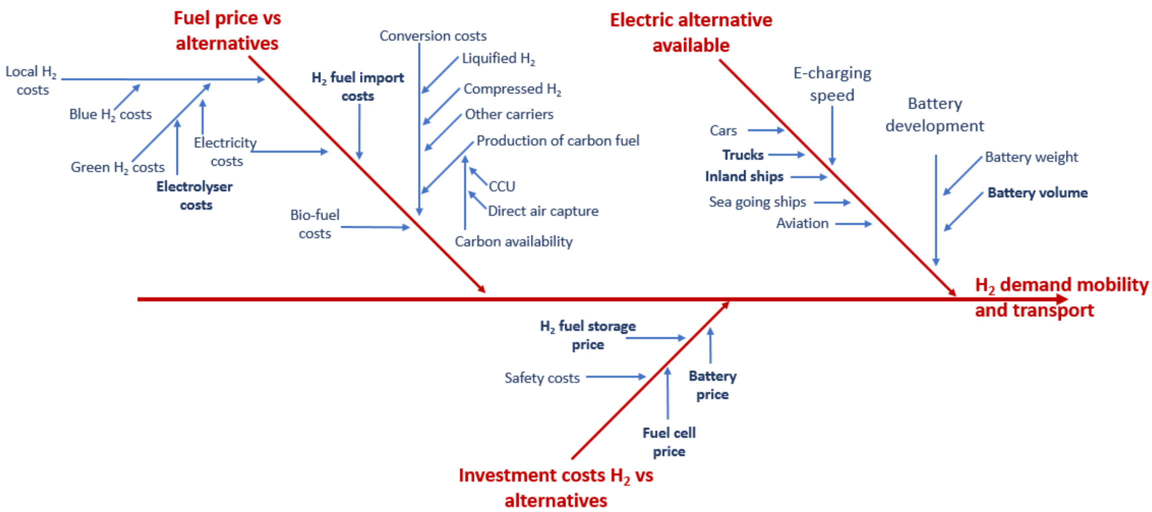


Figure 39: Fishbone mobility and transport

Annex G ETM Scenarios

Links to Energy Transition Model scenarios

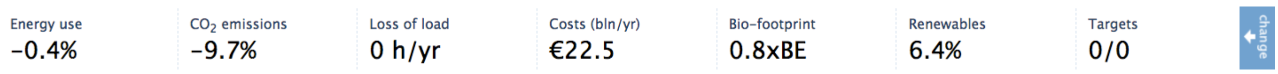
The ETM scenarios can be explored online. The following links lead to more detailed descriptions in the ETM:

- High case: https://pro.energytransitionmodel.com/scenarios/411379
- Low case: https://pro.energytransitionmodel.com/scenarios/411384

About the Energy Transition Model

The Energy Transition Model (https://pro.energytransitionmodel.com) has been used to support policy development, communication and education on the subject of energy transition for the past ten years. The ETM is a free to use, open source, online model that allows its users to create future energy scenarios for geographic regions of varying sizes, from supra-national to small villages. The ETM has been in continuous development since 2008 and covers the demand, supply and costs of over 45 energy carriers used for a wide range of commercially available technologies in all sectors of the economy. It also contains an hourly calculation of electricity load (demand, supply and flexibility) on five different grid levels, hydrogen (demand, supply and storage) and heat.

As an energy system simulation model its aim is to allow users to quickly explore a large range of options. To that end, the user is invited to make assumptions on how the future differs from the present. Each time a change is made, the ETM rapidly (response time <0.5 s) recalculates the entire system. A dashboard displays changes to a region's primary energy demand, CO_2-emissions, annual costs, security of power supply, renewability, etc. Furthermore, a large number of charts is available to display changes in particular (sub)sectors of the energy system and all calculated data are available for download as well.



Interactive dashboard in the Energy Transition Model

The ETM is continuously being improved by Quintel Intelligence in collaboration with a large number of partners. During the past ten years it has mostly been used in the Netherlands and Belgium to facilitate and accelerate the public debate on the energy transition. Funds for developing the ETM originate from different partner organizations with a stake in this discussion. The open source and transparent nature of the ETM ensures that all data, parameters, modelling logic and programming code is visible to the public. This makes the ETM ideally suited for co-development. Any development carried out in cooperation with any partner will be made available to all users of the ETM.

The ETM is used by many partner organisations to assist in their long-term planning, including Gasunie and TenneT. Recently, versions of the ETM have also been made available for Germany, Denmark, Spain, France, the United Kingdom and Poland, as well as for almost all provinces and municipalities within the Netherlands. This allows creating energy scenarios for a wide range of geographical scales. The ETM makes it possible to add up scenarios for different regions to explore potential synergies between these regions.