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Hydrogen in the Netherlands

A review of recent Dutch scenario studies

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1 Introduction

In this report we discuss the potential future role of hydrogen as energy carrier and feedstock in a low-carbon energy system, focusing on the Netherlands. Our previous meta-analysis in the context of the HyChain 1 [1] and Integrated Energy System Analysis [2] projects is updated with the findings of a few recent Dutch reports and studies but now only covers system analyses of the Netherlands. We provide a review of the projected range in hydrogen use across various sectoral applications based on 13 studies reported in the recent literature (see Appendix A for a list of the studies). Studies with a focus on other regions, for instance on Europe or the world, are used in the discussion in a qualitative and comparative manner. This analysis provides a range of projected hydrogen use in the Netherlands towards 2050. Some insights in the similarities and differences in assumptions and outcomes of the studies reviewed are discussed with regard to the future role of hydrogen use in a low-carbon energy system.

Today, around 8400 PJ (70 Mt) hydrogen is annually produced (see Box 1) and used worldwide, mainly in industry. The top four single uses of hydrogen (both pure and in mixed forms such as syngas) are: oil refining (33%), ammonia production (27%), methanol production (11%), and steel production via the direct reduction of iron ore (3%) [3]. In the Netherlands, around 175 PJ (1.5 Mt) hydrogen is produced and used, mainly in the industrial sector [4] [5] [6]. This includes around 117 PJ pure hydrogen (1.0 Mt) produced from various sources as well as hydrogen as part of gas mixtures, which are used and produced in various types of industrial processes. Based on two recent studies [5] [6], the distribution of hydrogen use in the Netherlands is similar as the global average (see above): for ammonia production (58-65 PJ), in refineries (59-66 PJ), for methanol production (12-18 PJ), and in other processes (34-42 PJ), such as hydrogenation, hydrogen peroxide production, glass manufacturing, metallurgy, and heat and power production.

Hydrogen use today is clearly dominated by industrial applications and this role may increase in the future. Hydrogen, however, also holds long-term promise in many sectors beyond existing industrial applications. The Hydrogen Council recently analyzed 35 hydrogen end use applications in transport (17), buildings (8), industry heat (6), and industry feedstock (4) [7]. For each of these applications, they assessed the total costs of ownership and compared these to alternative low-carbon solutions (e.g. battery vehicles, heat pumps) and conventional technologies (e.g. diesel-powered vehicles, gas boilers). They identified 22 applications where hydrogen, under the right conditions, can become a cost-competitive low-carbon solution before 2030. In addition, they discuss the break-even cost of hydrogen for these applications in 2030 and the related theoretical amount of energy, which these applications consume (see also Figure 7 and Figure 8 in appendix B). The role of hydrogen in these applications is highly location specific and depends for instance on the availability and costs of hydrogen and alternatives at that location.

In this report we analyze the current and future role of hydrogen in the Netherlands based on recent studies. We first discuss the potential of several hydrogen applications in five different sectors, i.e. industry, synthetic fuels, transport, built environment, and power production. We determine the range of hydrogen use in these sectors based on various scenario studies, of which some are substantiated by energy system modelling. These models are for instance used to simulate an envisioned future scenario (e.g. with Quintel's energy transition model (ETM)) or to optimize the costs of the energy system under a set of given scenario constraints (e.g. with TNO's OPERA model). Next, we present the total projected hydrogen use and discuss the systemic role of hydrogen in a carbon-neutral society. We finish with some general conclusions.

Box 1. Hydrogen production

Most hydrogen comes from fossil fuels (grey hydrogen). According to the Future of Hydrogen report (IEA 2019), hydrogen is mainly produced by natural gas reforming (75%) and coal gasification (23%) and its production consumes approximately 6% of global natural gas use and 2% of global coal use. Oil and electrolysis account for roughly 2% of global hydrogen production. Hydrogen production is responsible for 830 Mt per year of CO_2 emissions – corresponding to more than four times the current annual greenhouse gas (GHG) emissions of the Netherlands. In the Netherlands, 175 PJ hydrogen is produced and formed (or released) in pure form or as part of residual gases in various industrial processes in five industrial clusters and often directly fulfils hydrogen demand in these clusters. Some (private) interconnecting networks in and between these clusters, e.g. between Zeelandic Flanders and the Rhine-Meuse delta, and also to Belgium (and France) already exist. Hydrogen in the Netherlands is produced through reforming of natural gas, as byproduct of steam cracking of naphtha (olefin synthesis), during oil refining, by electrocatalytic brine conversion (chlorine production), and in steel manufacturing processes.

However, recent cost reductions in renewable electricity generation (for “green” hydrogen from electrolysis), developments in carbon capture and storage (CCS, for “blue” hydrogen from natural gas reforming), and progress in sustainable biomass availability (for “bio” hydrogen production from biomass gasification) may result in a growing number of alternative, low-carbon hydrogen production pathways (Hydrogen Council 2020). The (projected) costs and competitiveness of the different hydrogen production routes are discussed in various reports [3, 5] [14].

The power sector may function as an example of a system in which an energy carrier, namely electricity, is slowly decarbonized. Uptake of renewable electricity supply, for instance by the deployment of photovoltaics and wind turbines, is replacing fossil-based power generation and steadily decarbonizes the electricity system. The development of a hydrogen network infrastructure may unlock a broader utilization of hydrogen as a potentially renewable energy carrier even when starting off with fossil-based (grey or blue) hydrogen. Market uptake of low-carbon hydrogen production routes can soon initiate the decarbonization of hydrogen supply chains.

2 Hydrogen in 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. Hydrogen can, alike biomethane, be blended into the natural gas network for decarbonization. Alternatively, an increasing share of the network can be turned over to pure hydrogen. A more detailed assessment of industrial applications of hydrogen can be found in other reports [1] [8]. Hydrogen can be used in direct heating and indirect heating processes.

Hydrogen is not an energy source and being an intermediate energy carrier, often with a fossil origin, it is traditionally not considered in energy system analysis. Its existing role as feedstock likely continues in the future, although hydrogen use in the refining sector may decrease due to declining oil demand. The recent interest in renewable hydrogen use has triggered modelers and analysts to consider hydrogen as a separate energy carrier irrespective of its origin. The transition from current use to both existing applications and novel options is sometimes not clearly explained in the studies. Some studies only report about hydrogen use in industry, while other studies distinguish between energetic and feedstock use. Typically, feedstock use in 2050 is a combination of existing use of hydrogen and novel applications. Depending on the novel applications included in the studied scenario, hydrogen use as feedstock, for instance to produce steel, chemicals, and plastics (e.g. based on CO/CO_2 reduction processes), may in 2050 surpass existing levels of use. Industrial production of synthetic fuels, also referred to as power-to-fuels, is treated as a separate category.

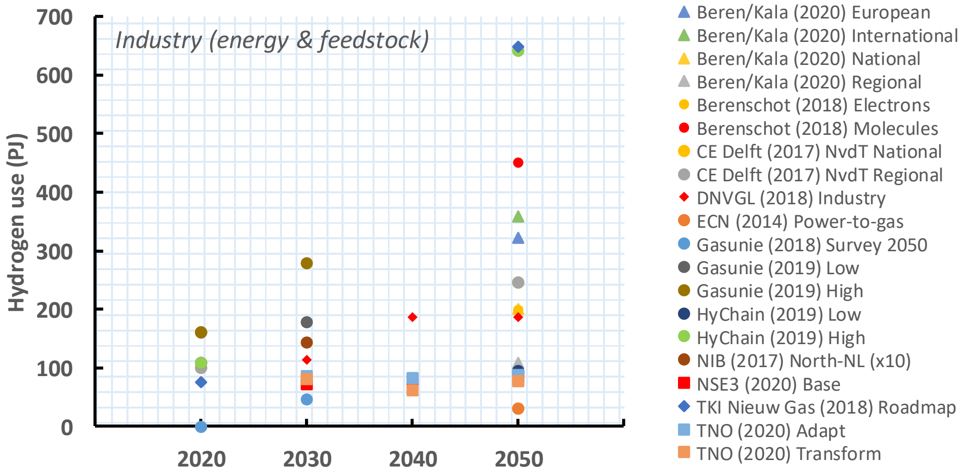

Figure 1. Hydrogen demand for industry

We show the total hydrogen demand of industry, which is a combination of energetic and feedstock use, from 2020 to 2050 according to the studies (Figure 1). The projections for 2050 range from nearly 100 PJ/yr, which is similar as the current level of pure hydrogen use, to more than 600 PJ/yr, more than tripling today's total production in pure and mixed form. Around 250 PJ/yr at maximum is for energetic use. The studies do not agree in their assumptions on the distribution of hydrogen use over energy and feedstock. Some report a substantial increase of energetic hydrogen use, while other studies project a minimal role for heating but do foresee an increase in hydrogen use as feedstock.

3 Hydrogen for synthetic fuel production

The conversion of biomass or CO_2 into biofuels and renewable synthetic fuels for transport applications, such as planes and ships, may demand substantial amounts of hydrogen in the future. Liquid synthetic fuels are often dedicated for international shipping and aviation. While some (especially recent) scenario studies do include international shipping and aviation in their analysis, others exclude these demand sectors because they do not contribute to the national emissions counting rules. The production of these fuels will increase hydrogen demand of industry, although in some studies this share of hydrogen use is ascribed to the transport sector. Here we consider these synthetic fuels as a separate category.

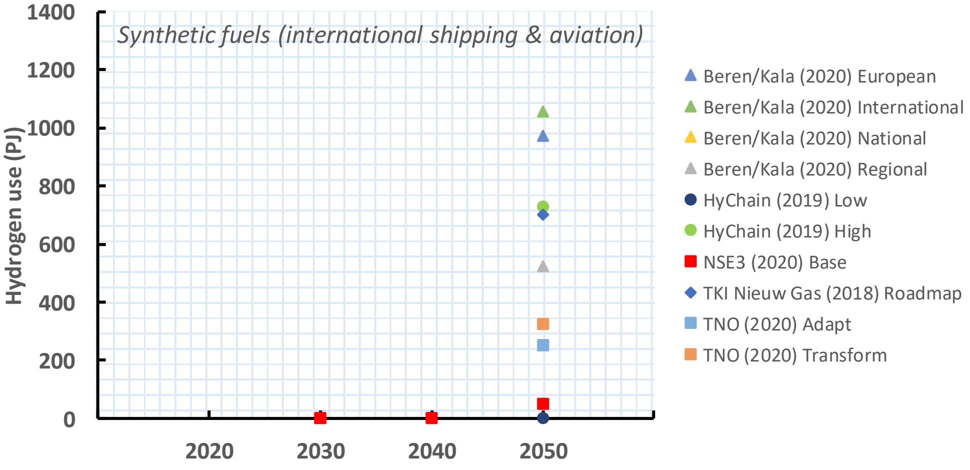

Figure 2. Hydrogen demand for synthetic fuel production[1]

Energy demand of international shipping and aviation plays an important and substantial role, currently around 660 PJ/yr, in the Dutch energy system. The range presented by the studies indicates the relative share of energy demand by this sector that is provided by hydrogen for the production of liquid synthetic fuels (Figure 2). Alternative liquid fuels for this application are fossil fuels like kerosene, diesel and heavy fuel oil, and biofuels.

4 Hydrogen for transport

In the transport sector, excluding international shipping and aviation, battery electric vehicles (BEVs) are expected to take over a high share of road transport. Also hydrogen plays often a significant role as fuel for transportation, mainly for fuel cells in heavy duty vehicles. Only a few studies foresee no role for hydrogen and expect a dominant role for electricity and biofuels. The projected range is broad, but the majority of the outcomes lies between 50 and 150 PJ/yr of hydrogen use for mobility (Figure 3). Total current use of energy in the transport sector equals approximately 500 PJ/yr [9].

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[1] *For the TNO scenarios, we calculated hydrogen use for synthetic fuel production by multiplying the energy content of the synthetic fuels by 1.21 (energy efficiency of 83%).*

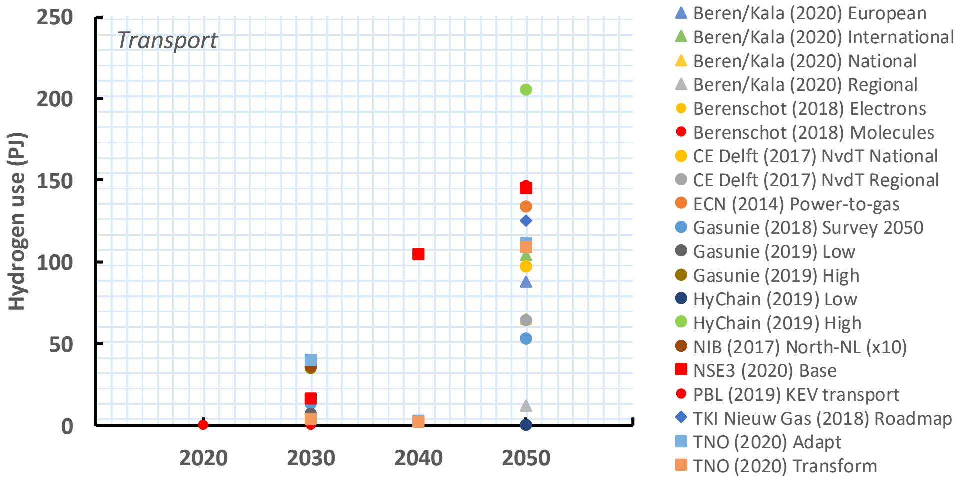

Figure 3. Hydrogen demand for transport

5 Hydrogen in the built environment

Hydrogen can be used in gas networks, either directly as pure hydrogen gas or mixed with natural gas or bio-methane. The distribution of hydrogen via the network allows it to directly supply energy for space and tap water heating, and in principle also for cooking in buildings. Especially for old and poorly isolated houses hydrogen can provide a low-carbon alternative for natural gas. Next to delivery at home level, hydrogen can also be applied in (peak) boilers for collective heating systems, such as local block heating for flats or central district heating networks. A more detailed overview of hydrogen options for the built environment has recently been published [10].

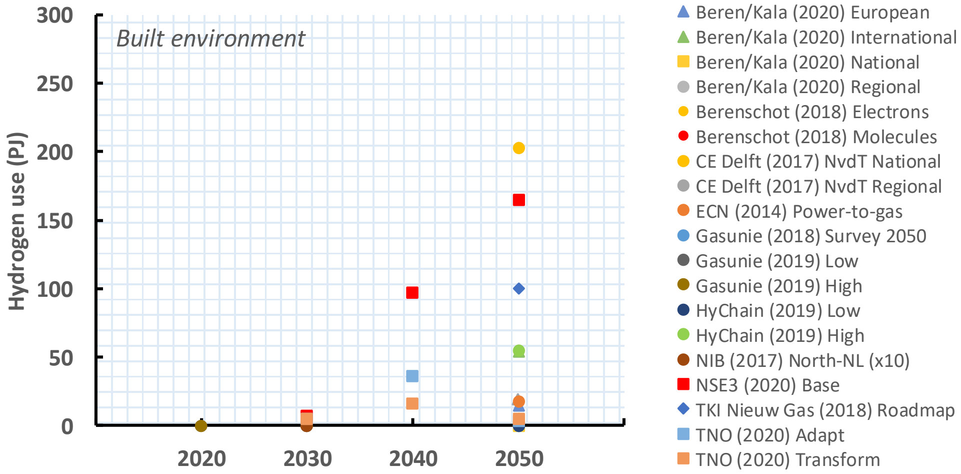

Figure 4. Hydrogen demand in the built environment

Total energy use by buildings in the form of electricity and natural gas is slightly below 350 PJ/yr in 2020. A decline is projected towards 2030 to around 300 PJ/yr mainly thanks to the use of heat pumps, improved insulation, and efficiency improvements of electric appliances [9]. Most studies do not expect a significant use of hydrogen in the built environment (<50 PJ/yr), although in four scenarios hydrogen use even exceeds 100 PJ/yr (Figure 4). In the latter cases hybrid heat pumps are (partly) fueled by hydrogen, instead of by bio-methane, and hydrogen also fuels (part of) the district heating networks.

6 Hydrogen for power production

A certain share of power generation should be (remain) dispatchable to provide the required flexibility to cope with the both daily and seasonal intermittency of renewable power generation. During periods with less sun and wind, gas turbines or stationary fuel cell systems, both running on hydrogen, can respond quickly to provide electricity and stabilize the grid. The future role of hydrogen for power generation remains uncertain, which is also displayed by the broad range of hydrogen use for this application in the studies (Figure 5). Some scenarios project the use of alternative options (e.g. demand response and international electricity trade) to stabilize the grid, which results in no or very low hydrogen demand for electricity generation. In other scenarios hydrogen plays a dominant role (more than 300 PJ/yr) as fuel to produce back-up power (and heat) in combined heat and power plants (CHPs) and gas-fired power plants.

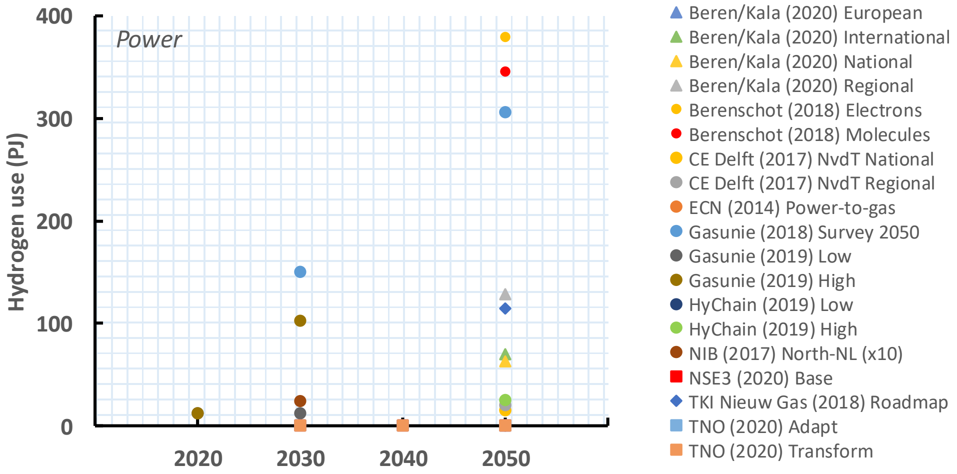

Figure 5. Hydrogen demand for electricity production

7 Total hydrogen use in the Netherlands

The previous sections reveal a broad range in potential applications of hydrogen use. The cumulative numbers are presented in Figure 6. Conservative estimates for 2050 project a hydrogen use of around 200 PJ/yr, while the highest projections go up to almost 1700 PJ/yr. In scenarios based on visions or simulation models (e.g. ETM), the total hydrogen use is typically higher than in scenarios that are modelled with a static cost optimization model (e.g. OPERA). This difference results likely from the fact that in visions and simulation models hydrogen use is typically determined exogenously, while in optimization models this use is often endogenously calculated, i.e. as a result of competition between different options. Some international outlooks foresee no substantial market for green hydrogen before the half of this century (e.g. [11], [12]. For example, in the Sky scenario [12], which gives a projection until 2100, hydrogen use starts to develop from 2040 onwards and is deployed at scale only in the second half of the century. Projections may, however, change rapidly over time as illustrated by the World Energy Outlook (WEO) reports of the IEA. In WEO 2017, the word "hydrogen" occurs in 40 instances and in tables no numbers are included about the contribution of hydrogen in final energy use up to 2040 [13]. In WEO 2019, hydrogen is mentioned 373 times and also appears in the final energy consumption table [11]. The IEA projects a use of hydrogen as a fuel and produced from dedicated hydrogen production facilities of nearly 3 EJ/yr in 2040 in the Sustainable Development Scenario. Overall, we observe an upward trend in the projected hydrogen demand over time. The broad range of the projections reveals that there exist large uncertainties on the future role of hydrogen in the energy system. Studies with the highest projections typically assign a significant amount of hydrogen use for the production of synthetic fuels. This application generally exceeds 50% of the total hydrogen demand as observed in the studies.

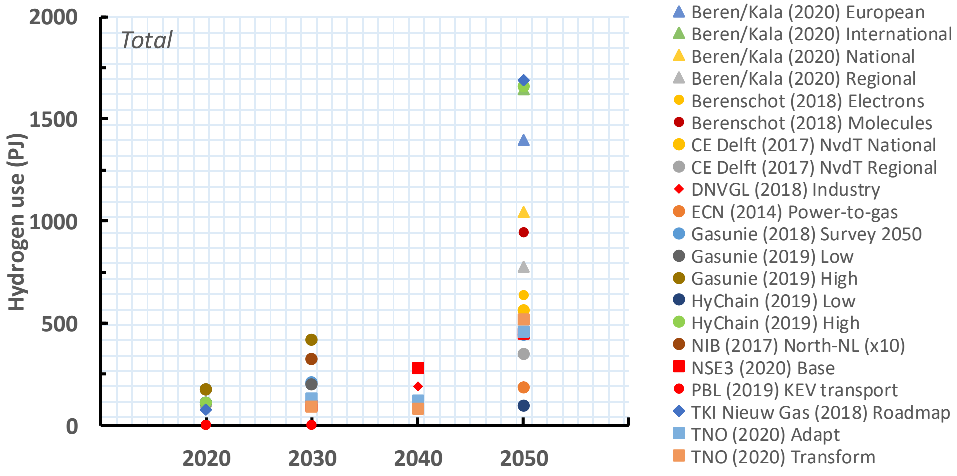

Figure 6. Total projected hydrogen use in the Netherlands.

The availability of hydrogen for a multitude of applications may result in cost-effective CO_2 emission reductions in several sectors, and especially those that are otherwise difficult to abate – such as logistics, industrial heating and industry feedstock. A more adequate assessment of the future role of hydrogen in the energy system as a whole, also concerns system aspects such as the reliability or balancing of the energy system. For instance, during periods of excess power production from sun and wind, electricity can be converted into hydrogen by ramping up electrolyzer capacity as a demand response option to balance the electricity grid. Hydrogen can also play a role as a seasonal storage option for the energy system as a whole – including electricity, gas and heat – thereby enhancing the reliability and balancing of the energy system based largely on renewable (intermittent) energy sources. As such, increased hydrogen use may facilitate a higher uptake of renewable power supply in the system, because the generated power is, once converted into hydrogen, not capped by maximum demand for electricity. Hydrogen may have the ability to contribute to a more reliable energy system in terms of emission reductions, grid stability, and energy security.

8 Conclusion

A large number of recent studies have considered the potential uses of hydrogen and its size. The estimates show a large bandwidth due to differences in scope, modelling approach, and most likely also in underlying assumptions. Especially whether or not to include hydrogen for the production of synthetic bunker fuels and products in the chemical industry based on hydrogen and CO_2 has a major impact. Without these categories, the size of hydrogen demand in 2050 for the Netherlands generally ranges from the current industrial level up to an average of approximately 500 PJ (46 bcm), while including these categories values can reach well above 1000 PJ (>93 bcm). Furthermore, study results on average show a relatively even distribution across the sectors industry, power, transport and built environment.

9 References

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[11] IEA, "World Energy Outlook 2019," 2019. Available from: https://www.iea.org/reports/world-energy-outlook-2019.

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[13] IEA, "World Energy Outlook 2017," 2017. Available from: https://www.iea.org/reports/world-energy-outlook-2017.

[14] World Energy Council, "Hydrogen - Industry as catalyst," 2019. Available from: http://www.wereldenergieraad.nl/wp-content/uploads/2019/02/190207-WEC-brochure-2019-A4.pdf [Accessed June 2020].

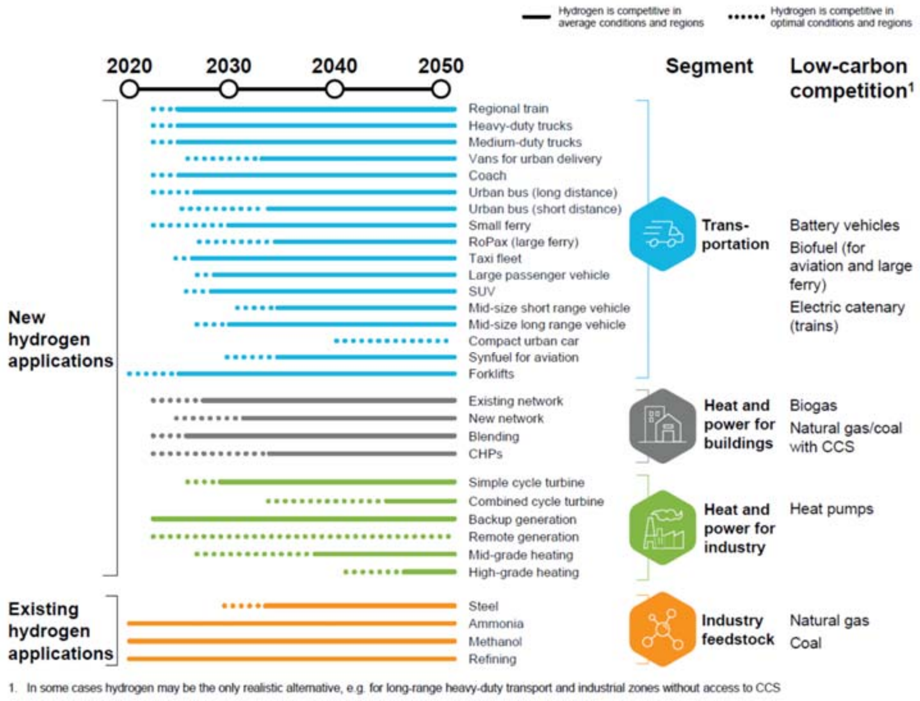
10 Appendix A

List of the analyzed studies

Berenschot (2018)	den Ouden, B., Graafland, P., Warnaars, J., Berenschot, 2018. “Electronen en/of Moleculen – twee transitiepaden voor een CO_2 neutrale toekomst”. Both the Electronen (Electons) and Moleculen (Molecules) scenario are used in our meta-analysis.
Beren/Kala (2020)	den Ouden, B., Kerkhoven, J., Warnaars, J., Terwel, R., Coenen, M., Verboon, T. Tiihonen, T., Koot, A., Berenschot & Kalavasta, 2020. “Klimaatneutrale energiescenario’s 2050, Scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030-2050.” The Regional, National, European, and International scenario are part of our meta-analysis.
CE Delft (2017) NvdT	Afman, M. and Rooijers, F., CE Delft, Netbeheer Nederland, 2017. “Net voor de toekomst; Een vooruitblik op de energievoorziening in 2050”; Net voor de toekomst; Achtergrondrapport, 2017. Scenarios “Regie Nationaal” (Nat) and “Regie Regionaal” (Reg) are part of our meta-analysis.
DNV-GL (2018)	Gersen, S., van Essen, M., Slim, B., DNV-GL. “Verkenning naar mogelijkheden om aardgas te vervangen in industriële verhittingsprocessen," 2018. Only energetic use for industry.
ECN (2014)	de Joode, J., Daniëls, B., Smekens, K., van Stralen, J., Dalla Longa, F., Schoots, K., Seebregts, A., Grond, L., Holstein, J., ECN-E14026, 2014. “Exploring the role for power-to-gas in the future Dutch energy system”. The restricted CCS and 85% CO_2 reduction scenario is used in our meta-analysis.
Gasunie (2018)	Gasunie, 2018. “Survey 2050 – Discussion paper”.
Gasunie (2019)	Gasunie, 2019. “Waterstof vraag en aanbod nu – 2030”. The high and low estimates of the range are part of our meta-analysis.
HyChain (2019)	Knoors, B., Katawar, P., Wirtz, A., Berkhout, J., Detz, R., Weeda., W., Institute for Sustainable Process Technology (ISPT), 2019. “Hydrohub HyChain 1: Energy carriers and Hydrogen Supply Chain: Assessment of future trends in industrial hydrogen demand and infrastructure”. The high and low estimates of the range are part of our meta-analysis.
NIB (2017) North-NL	Northern Innovation Board (NIB), 2017. “Green hydrogen economy in the Northern Netherlands”. The data is multiplied by 10 to allow a better comparison with data of studies for the Netherlands as a whole.
NSE (2020) Base	van Stralen, J., Sipma, J., Gerdes, J., TNO, 2020. “North Sea Energy (NSE), D1.2 – An analysis of the value of offshore hydrogen production in relation to alternatives, The role of hydrogen as part of a portfolio of climate change mitigation solutions for the Netherlands towards 2050.”
PBL (2019) KEV	Planbureau voor de Leefomgeving (PBL), 2019. “Klimaat- en Energieverkenning 2019”. Only values for hydrogen use in the transport sector are used in our meta-analysis.

TKI Nieuw Gas (2018)	Gigler, J, Weeda, M., TKI Nieuw Gas and ECN, 2018. “Outlines of a Hydrogen Roadmap”.
TNO (2020)	Scheepers, M., Gamboa Palacios, S., Jegu, E., Pupo Nogueira De Oliveira, L., Rutten, L., van Stralen, J., Smekens, K., West, K., TNO 2020 P10338, 2020. “Towards a sustainable energy system for the Netherlands in 2050”. Scenarios ADAPT and TRANSFORM are part of our meta-analysis.

11 Appendix B



1. In some cases hydrogen may be the only realistic alternative, e.g. for long-range heavy-duty transport and industrial zones without access to CCS

Figure 7. Cost competitiveness trajectories of hydrogen applications [7].

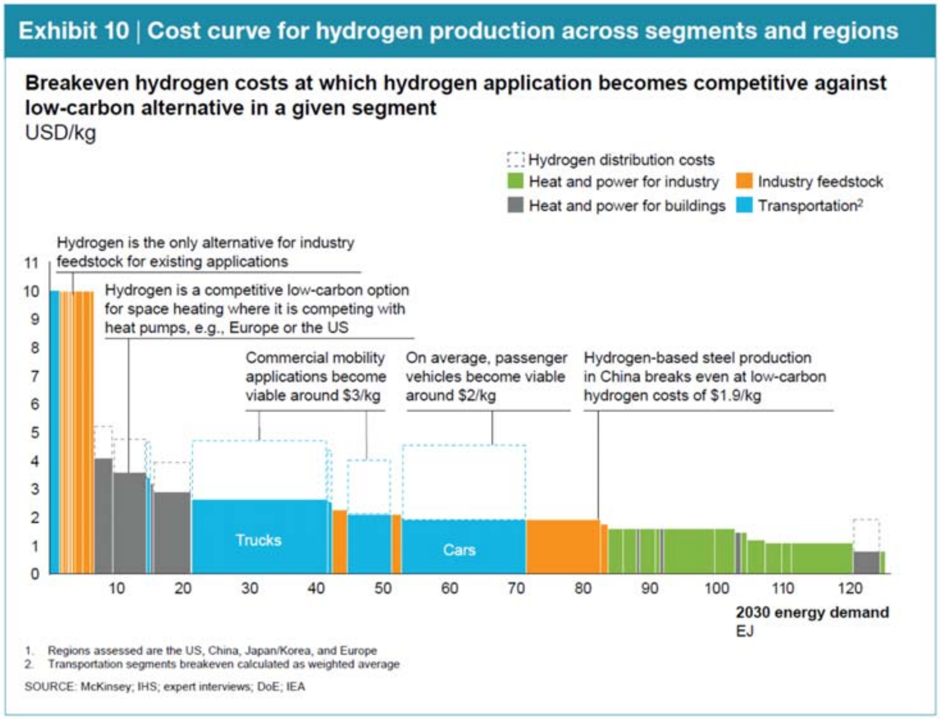


Exhibit 10 | Cost curve for hydrogen production across segments and regions

Breakeven hydrogen costs at which hydrogen application becomes competitive against low-carbon alternative in a given segment
USD/kg

1. Regions assessed are the US, China, Japan/Korea, and Europe
2. Transportation segments breakeven calculated as weighted average

SOURCE: McKinsey; IHS; expert interviews; DoE; IEA

Figure 8. Cost curve for hydrogen production across segments and regions [7].