WORKING PAPER 2021-28

JULY 2021

Hydrogen for Heating? Decarbonization Options for Households in the Netherlands in 2050

Authors: Chelsea Baldino, Jane O'Malley, Stephanie Searle (ICCT); Adam Christensen (Three Seas Consulting)

Keywords: low-carbon heating, household heating cost, hydrogen, renewable electricity, fuel cell, hydrogen boiler, heat pump, hybrid heat pump, electrolysis, steam methane reforming

Summary

To align with the National Climate Agreement, Dutch municipalities must devise a "transition vision for heating" ("transitievisie warmte") by the end of 2021 to phase out natural gas from heating by 2050. Possible decarbonization options for the heating sector include the use of hydrogen, renewable electricity, or a combination of the two. At the same time, energy poverty impacts 1 million households in the Netherlands, so it is important to consider the cost of these options. In this study, we compare the cost of several low-greenhouse gas (GHG) or GHG-neutral residential heating pathways in the Netherlands in the year 2050: (1) hydrogen boilers, (2) hydrogen fuel cells with an auxiliary hydrogen boiler for cold spells, (3) air-source heat pumps using renewable electricity, and (4) heat pumps with an auxiliary hydrogen boiler for cold spells. Our analysis includes zero-GHG hydrogen produced from renewable electricity using electrolysis and low-GHG hydrogen from steam-methane reforming (SMR) using natural gas combined with carbon capture and storage (CCS).

Figure ES1 shows that we find heat pumps to be the most cost-effective of the assessed residential heating technologies in the Netherlands in 2050. All heat pump scenarios are at least 50% lower in cost than those where hydrogen is the primary form of heating in a boiler or fuel cell, as shown in the bars in the figure. In a sensitivity analysis, we find that heat pumps would still be more cost-effective than any hydrogen heating technology, even if natural gas costs were 50% lower or renewable electricity prices 50% higher in 2050 compared to our central assumptions. While electrolysis hydrogen is not produced at scale today, we find that electrolysis hydrogen will be cost-competitive with SMR + CCS hydrogen in the Netherlands in 2050. Where the lifecycle GHG reduction potential

www.theicct.org

communications@theicct.org

twitter @theicct

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

Acknowledgments: This work was generously funded by the European Climate Foundation. Responsibility for the information and views set out in this report lies with the authors. The European Climate Foundation cannot be held responsible for any use which may be made of the information contained or expressed herein. Thanks to Peter Mock, Femke de Jong, Renée Bruel, and Atse van Pelt for their reviews.

compared to fossil fuels is shown as a percent (see triangles in the Figure), we find that SMR + CCS hydrogen could reduce greenhouse gas (GHG) emissions by 69-93% compared to natural gas if improvements are made in the future to reduce the GHG intensity of this pathway. All pathways using renewable electricity have a zero or near-zero GHG intensity. Our findings support many municipalities' decisions to pursue heat pumps as the primary decarbonized heating solution for Dutch residences.

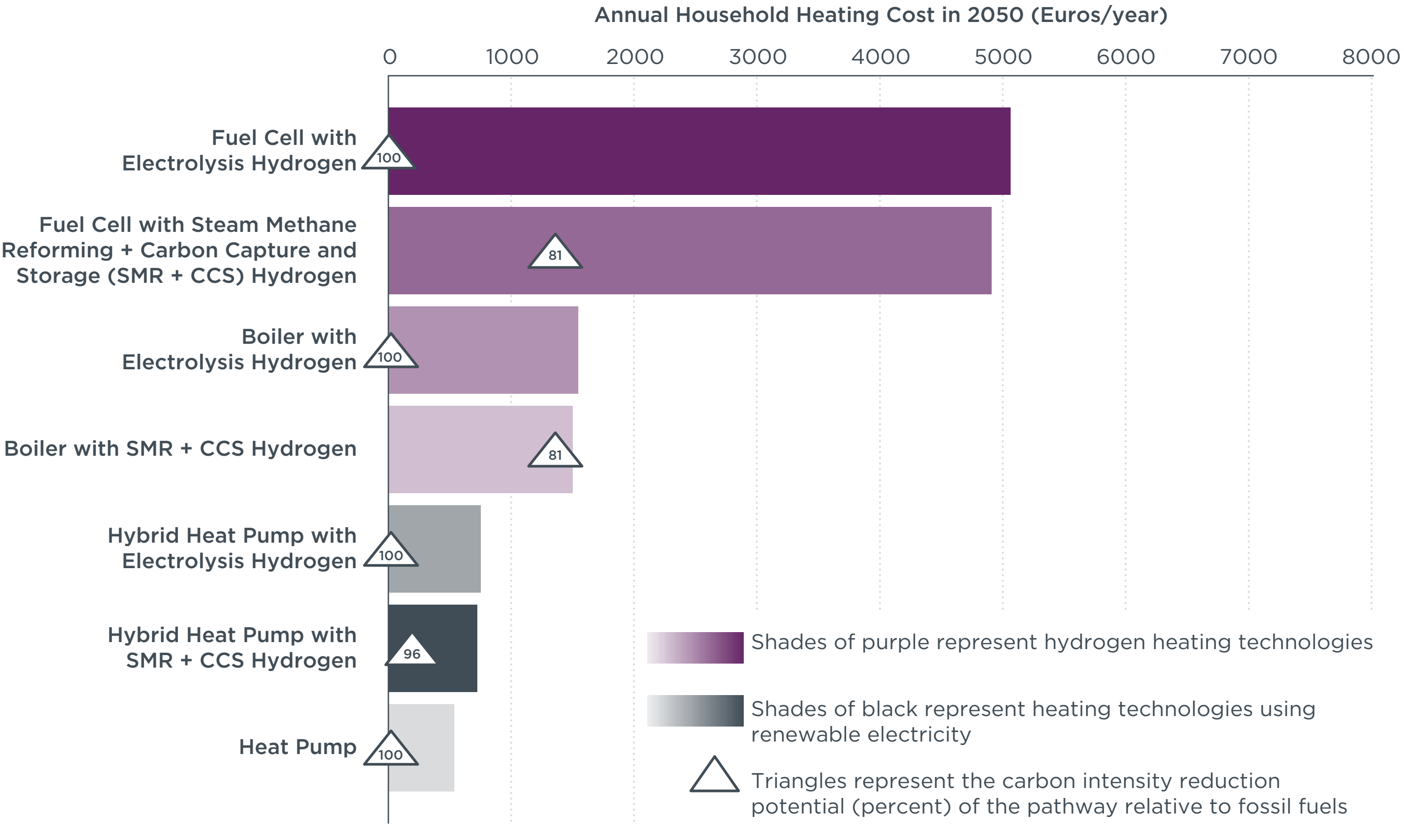

Figure ES1. Cost comparison (in euros) and greenhouse gas intensity reduction potential of different technology options for heating a household for one year in the Netherlands in 2050

Introduction

The Netherlands has set a goal of reaching climate neutrality in its built environment by 2050 (Voortgangsoverleg Klimaatakkoord, 2021). Achieving this will require a major transformation in energy use in the heating sector. Nearly 13% of energy consumption in the Netherlands goes to heating residences, and in 2018, natural gas was used to meet 90% of residential heating demand in the Netherlands (International Energy Agency, 2020; CBS, 2021). As a part of the National Climate Agreement, Dutch municipalities must devise a "transition vision for heating" ("transitievisie warmte ") by the end of 2021 to phase out natural gas from heating by 2050 ("Van het gas af," 2020). Forty-six municipalities in the Netherlands have received government funding to pilot programs disconnecting citizens from the natural gas grid and investing in alternative heating technologies (Dimitrova, 2020). Amsterdam, for example, plans to be natural gas-free by 2040 (Bieckmann, 2018). Possible energy options to decarbonize the heating sector include hydrogen, renewable electricity, or a combination of the two.

The Dutch government envisions that heat pumps will play an important role in heating buildings in the Netherlands in the years leading up to 2030 (van t' Wout, 2021). Heat pumps are a mature technology that can utilize renewable electricity directly for heating at effective efficiencies of 250% to 400%. Heat pumps have efficiencies greater than

100% due to the fact that they do not generate heat, but transfer already existing heat (Moya, Tsiropoulous, Tarvydas, Nijs, 2019).

At the same time, some stakeholders in the Netherlands push for hydrogen in heating, and the government has an ambitious strategy to ramp up hydrogen production. In 2020, the Dutch government released a policy agenda for their national hydrogen strategy (Ministry of Economic Affairs and Climate Policy, 2020b). Electrolysis hydrogen (also known as “green” hydrogen) from renewable electricity is one low-greenhouse gas (GHG) hydrogen option included in the policy agenda. Producers of electrolysis hydrogen can apply for government subsidies and aid, and the government is considering an obligation to integrate electrolysis hydrogen into the natural gas grid (In de Braekt and Waverijn, 2020). Additionally, the Dutch government is building a partnership with the German government and the German state of North Rhine-Westphalia for electrolysis hydrogen production and transport (Eriksen, 2020).

While the Netherlands scales up the production of electrolysis hydrogen before 2030, the Dutch hydrogen policy agenda states that low-GHG hydrogen from fossil gas will also be necessary to meet hydrogen demand. This could include hydrogen produced from natural gas that undergoes steam-methane reforming (SMR) and carbon capture and storage (CCS) (also known as “blue” hydrogen). The government allows providers of carbon capture and storage technology to compete for government subsidies.

Energy poverty affects 1 million households in the Netherlands, so the cost of different heating strategies is an important consideration (Sia Partners, 2017). In this study, we assess the annual cost of heating a typical single-family home in the Netherlands in the year 2050 using low-GHG hydrogen, renewable electricity, or a mixture of both energy sources. This analysis complements our other studies addressing the same question in the UK, Germany, and the EU as a whole (Baldino et al., 2020, Baldino et al., 2021a, Baldino et al., 2021b). We draw upon the methodology and assessment developed by Baldino, O’Malley, Searle, Zhou & Christensen (2020) on the most commercially mature technologies for hydrogen. This includes two scenarios that depend on hydrogen for heat, one a boiler heated using SMR + CCS hydrogen or electrolysis hydrogen, and another using a fuel cell and an auxiliary hydrogen boiler for cold spells. We also include two scenarios relying predominantly on heat pumps using renewable electricity to heat homes in 2050, one in which the home is heated solely by the heat pump and another including an auxiliary hydrogen boiler to supplement the heat pump on cold weather days. In all scenarios we assume wind or solar energy is used for renewable electricity. We also assess the lifecycle GHG impacts of each of these heating pathways.

Methodology

We utilize the same methodology and assumptions as Baldino et al. (2020), except for these differences:

Hydrogen production costs

We assume that all hydrogen produced from natural gas will be produced domestically in the Netherlands. This is because in 2020 the government stated that, despite the phase-out of extraction from the Groningen gas field, extraction from smaller gas fields, rather than imports, will be sufficient to meet natural gas demand in the Netherlands in the future (Ministry of Economic Affairs and Climate Policy, 2020a). We assume that SMR plus carbon capture and storage (CCS) will be the primary technology used to produce hydrogen from natural gas in 2050, and we follow the methodology for calculating this production cost detailed in Baldino et al. (2020). We project the price of wholesale natural gas for the Netherlands in 2050 based on historical prices and expected prices in 2030 and 2035. We estimate a typical gas mark-up fee including distribution and grid fees by comparing current Dutch retail and wholesale prices for natural gas (ECN, n.d.; European Commission, 2020).

We base the production costs for renewable hydrogen from electrolysis on a recent ICCT study (Christensen, 2020). In this study, production costs are based on wind and solar capacity factors from a study from the European Commission's Joint Research Centre. In this assessment, we update solar and wind capacity factors from the JRC, which we used to adjust the cost of the electrolysis hydrogen (F. Monforti- Ferrario, personal communication, December 15, 2020).

Hydrogen transport

Pipelines or trucks could deliver hydrogen to homes. We assume pipelines would be used if hydrogen were the primary energy source for heating in the Netherlands, because transporting fuels by pipeline is generally more economical than transporting by other means when demand is high, whereas truck transport may be more economical when demand is low. Therefore, when hydrogen is used in fuel cells and boilers, we assume that hydrogen could be transported via pipeline by repurposing today's natural gas pipeline network at approximately the same capacity. Existing pipelines would generally need to be retrofitted or rebuilt depending on the material, since not all material used in natural gas pipelines is compatible with hydrogen. Following our methodology in Baldino et al. (2020), we take the current natural gas transmission pipeline length from Astorri et al. (2018) and distribution pipeline length from Holland Logistics Library (2020). In order to levelize the cost of pipeline retrofitting per kg hydrogen supplied, we assume 2050 hydrogen demand will be the same as we currently expect for natural gas in 2050 in a business-as-usual scenario. We use the EU Reference Scenario projection for total natural gas demand in the Netherlands in 2050 (European Commission, 2016). We amortize the total pipeline retrofitting cost over 30 years. We expect that utility companies and pipeline operators would charge a fee for the use of pipelines and assume that this fee would be the same as present-day gas distribution fees for natural gas in the EU. We estimate this fee as the difference between wholesale and retail (for residential users) natural gas prices, using Eurostat (European Commission, 2020) and ECN (n.d.).

In scenarios where auxiliary hydrogen boilers supplement heat pumps, we expect that hydrogen is more likely to be transported by truck, due to lower demand. To estimate a typical driving distance for hydrogen transport trucks, we assume that SMR would take place in Rotterdam and the liquid hydrogen would travel by truck to Amsterdam, a population center. We then estimate the cost of trucking over this distance and apply that to the cost of supplying hydrogen to auxiliary boilers in the Netherlands as a whole. Although this is a simplification of trucking distances, we find that our overall hydrogen cost estimate is not sensitive to the distance parameter because most of the cost of transporting hydrogen by truck is generated in the liquefaction step, which is necessary regardless of trucking distance. Baldino et al. (2020) contains a sensitivity analysis of trucking distance on the final cost of heating.

Residential heating technology and cost

We assess four heating scenarios for heating single family houses. We focus on single family homes, which comprise most of the housing stock in the Netherlands (ACCESS, 2018). Two of our scenarios rely entirely on hydrogen: in one, we assume hydrogen is combusted in a boiler, while in the other we assume hydrogen is used in a fuel cell plus an auxiliary hydrogen boiler for cold spells. Two scenarios use renewable electricity in a heat pump. In one, we assume a heat pump using 100% renewable electricity can meet all heating demand, since climate change might decrease cold spells in the Netherlands. The other is a hybrid heat pump scenario, in which we assume an auxiliary hydrogen boiler is needed for cold spells, in case the heat pump alone cannot meet all of the demand. These scenarios are also relevant when considering district heating for multiple households, since similar heating technologies could be used at a larger scale.

We retrieve household space heating demand in 2015 from Fleiter et al., 2017. To determine the time that an auxiliary hydrogen boiler could be needed to supplement either a heat pump or fuel cells, we conduct an analysis of daily average temperatures using typical meteorological year data in Amsterdam from 1982- 1999 (American Society of Heating, Refrigeration, and Air-Conditioning Engineers, 2001). We calculate that a heat pump or fuel cell could be used to meet 80% of heating demand and the remainder of the demand would be met with an auxiliary boiler. We do not incorporate heat storage in our analysis. Fleiter et al. projects an overall 25% reduction in heating demand from 2015 to 2050 across the 14 EU member states it assesses, so we reduce 2015 residential space heating demand by this amount in our study.

Fuel cells produce heat, but most of the energy generated in a fuel cell reaction emerges in the form of electricity. We assume that this electricity would be used to meet the electricity demand of the residence, and the excess would be sold to electricity utility companies. We derive electricity demand for residences in 2050 from Klaus, Vollmer, Werner, Lehmann, & Müschen (2010), assuming that demand in German residences is representative of that of the typical residence in the Netherlands. We assume that excess electricity production would be sold to utility companies at the average wholesale price for renewable electricity in the Netherlands in 2050, using our projection of renewable electricity prices in Searle and Christensen (2018).

Results

Our analysis shows that all air-source heat pump scenarios cost less than the hydrogen-only technologies for heating a single-family household in the Netherlands in 2050, when all costs are included. This is illustrated in Figure 1, where the bars show the annualized cost of the different heating options in the Netherlands in 2050. All heat pump scenarios cost at least 50% less than the lowest-cost hydrogen technology, which is a boiler using SMR + CCS hydrogen. We find that a fuel cell using SMR + CCS hydrogen is 9 times more expensive than using a heat pump alone and 3 times more expensive than using a hydrogen boiler.

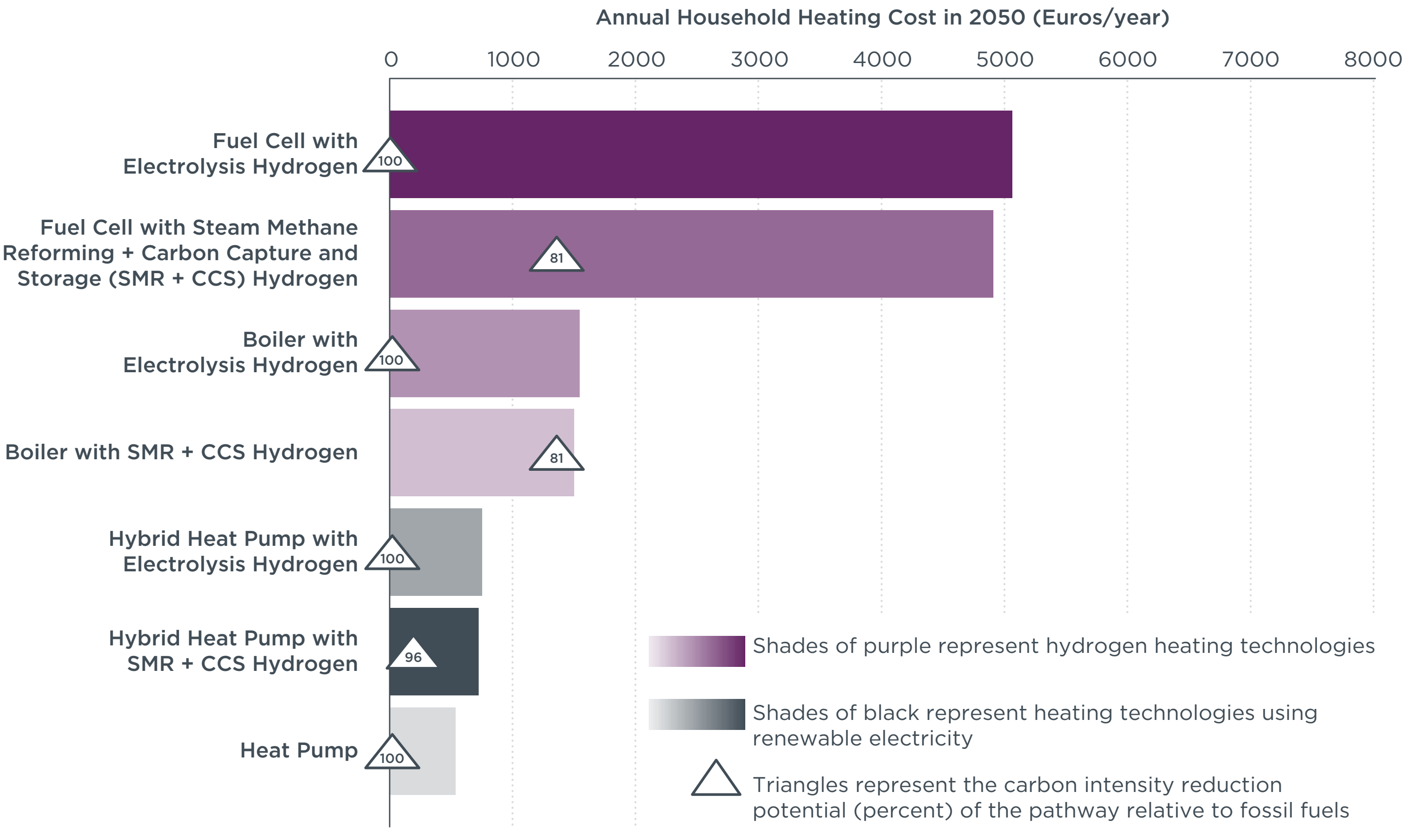

Figure 1. Cost comparison (in euros) and greenhouse gas intensity reduction potential of different technology options for heating a household for one year in the Netherlands in 2050

We find that in the Netherlands, electrolysis hydrogen and SMR + CCS hydrogen cost nearly the same. However, there is a significant difference in the GHG intensities between the two types of hydrogen, which are shown in the triangles in Figure 1. All pathways based on renewable electricity from wind and solar, including heat pumps and electrolysis hydrogen, provide a 100% GHG reduction relative to natural gas. SMR + CCS hydrogen has been estimated to deliver 42-61% GHG savings compared to fossil fuels at present (Baldino et al., 2020). In our analysis, we assume that the environmental performance of the pathway will improve to 2050. In particular, we assume some of the low-GHG hydrogen will be used as a process fuel instead of natural gas, as is the practice today. Given these assumed improvements, we find that the SMR + CCS pathway can provide a 69-93% reduction in GHG intensity compared to natural gas (represented as an average GHG reduction of 81% in Figure 1). The range in greenhouse gas reduction potential for the pathways using SMR + CCS hydrogen reflects both a range of possible carbon capture efficiencies (70%-90%), as well as a range of possible upstream methane leakage rates during natural gas production and transport (0.5-2%) (Parkinson et al., 2019). We calculate that in the hybrid heat pump pathway, the boiler would be used 20% of the year, so the GHG intensity for this pathway using SMR + CCS hydrogen is a weighted average of the renewable electricity needed for the heat pump and the hydrogen needed for the auxiliary hydrogen boiler. Baldino et al. (2020) explains how we derive these GHG intensities in more detail.

Figure 2 shows the breakdown in total costs for heat pump and SMR + CCS pathways, including input energy (hydrogen or renewable electricity), capital expenses (CAPEX) and operating expenses (OPEX). We find that the input energy (hydrogen or renewable electricity) accounts for the majority of overall cost for each pathway. While the CAPEX of a heat pump is greater than the CAPEX of a hydrogen boiler, the overall annualized expense for heat pumps is lower due to lower energy costs. For the hydrogen boiler pathway, OPEX is larger than CAPEX because boilers require annual maintenance. CAPEX represents the second-largest cost component for all other pathways. The energy cost shown for the fuel cell pathway is the net cost, subtracting the revenue from selling excess electricity to the grid. While households using fuel cell heaters receive a reduction in energy costs because of the excess electricity they produce, the reduction is not great enough to make the fuel cell heater cost competitive with the other pathways.

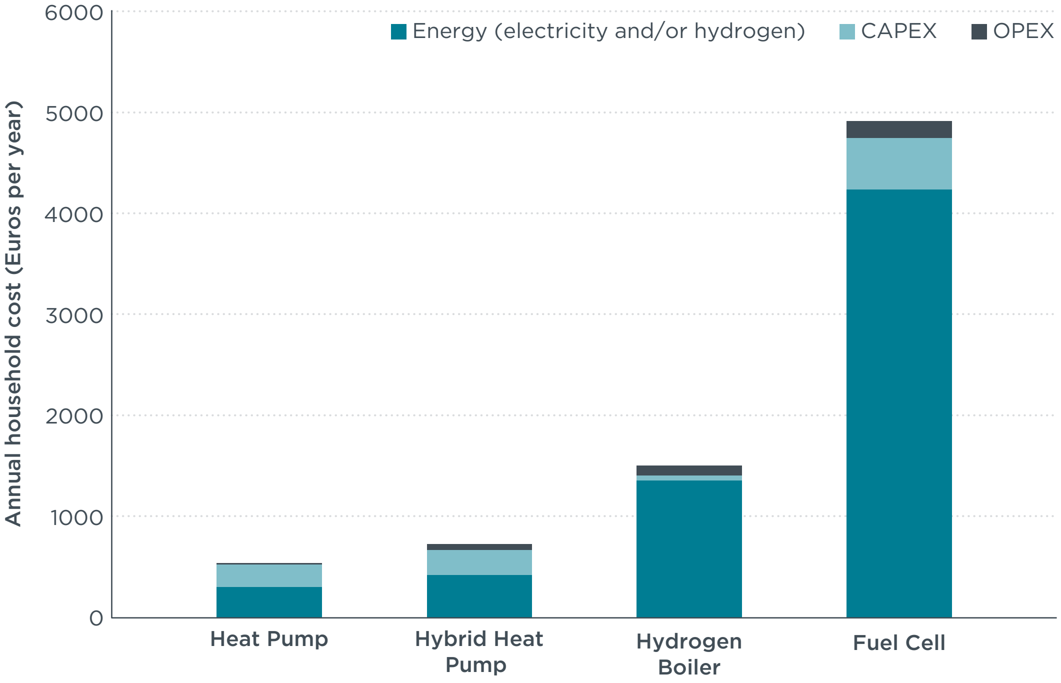

Figure 2. Cost components (euros) of heating pathways for one year in the Netherlands in 2050

Note: The cost of energy for the fuel cell scenario is net of excess electricity generation that is sold to the grid. For the pathways using hydrogen, the hydrogen is from SMR + CCS.

The cost of input energy (hydrogen and renewable electricity) makes up the majority of the cost for each of the pathways in our analysis, as Figure 2 illustrates. Since the cost of energy in 2050 is difficult to predict, we conduct a sensitivity analysis in which we vary energy prices to see how this impacts the cost of the different heating pathways, which we show in Figure 3. Error bars represent a 50% decrease and increase, respectively, in all energy-related costs for all scenarios except fuel cells using SMR + CCS hydrogen. We see an increase or decrease in the total cost of heat pump and hydrogen boiler scenarios of 20-30% compared to when we use our central energy price assumptions. As for the fuel cell scenario using SMR + CCS hydrogen, the error bars represent opposite changes in input renewable electricity and natural gas costs. The lower bar represents a case where renewable electricity prices are 50% higher (providing more revenue when consumers sell electricity is back to the grid compared to the main scenario) and natural gas prices are 50% lower, and the upper bar represents the opposite. In the SMR + CCS hydrogen scenario, the sensitivity analysis revealed a variation in total costs of 36% compared to the central scenario.

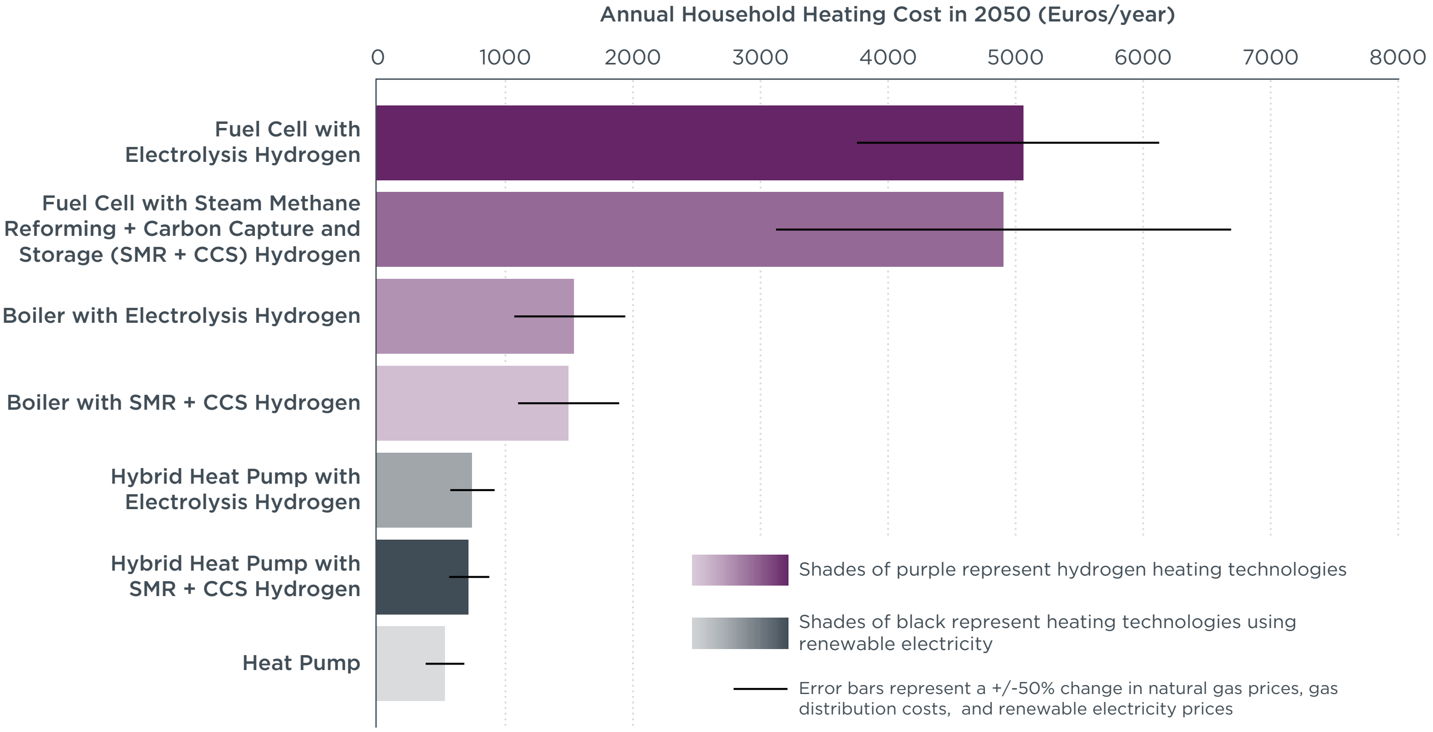

Figure 3. Sensitivity analysis (shown in error bars) on the cost of household heating

Our sensitivity analysis illustrates that all heat pump scenarios would remain the most cost-effective option even with 50% higher renewable electricity prices and 50% lower natural gas prices and gas distribution costs compared to our central assumptions. The cost advantage of heat pumps would increase were natural gas prices and gas distribution fees higher or renewable electricity prices lower. We find that none of the fuel cell scenarios become cost competitive with the other pathways even with these large changes in energy price assumptions.

Discussion

Of the options we assess, we find that heat pumps will be the most cost-effective heating solution for Dutch residences in 2050. This finding is robust within the bounds of our sensitivity analysis, and holds even if an auxiliary hydrogen boiler is needed to supplement a heat pump. In addition, heat pumps using renewable electricity provide a 100% reduction in GHG intensity relative to fossil fuels. While electrolysis hydrogen heating pathways can provide equally strong climate benefits, these pathways are at least twice as expensive as using a heat pump, even with an auxiliary hydrogen boiler. SMR + CCS hydrogen heating pathways cost the same as those using electrolysis hydrogen, but these pathways can only provide a 69-93% GHG reduction compared to fossil gas. We find that among the hydrogen heating pathways, hydrogen boilers cost less than fuel cells.

Our findings are valuable for municipalities in the Netherlands deciding how to decarbonize heating by 2050. In fact, heat pumps are one of the options municipalities are favoring to decarbonize heat, which is a strategy supported by our findings ("Van het gas af," 2020). In order to help achieve the goal of phasing out natural gas in heating, municipalities are asking the national government to remove subsidies for fossil fuels and instead use these funds to support homeowners who purchase low-GHG heating technologies and improve home insulation ("Van het gas af," 2020). A European Commission-funded case study in the Netherlands demonstrated the importance of public support schemes to help pay back the investment cost of heat pumps (Simonelli and Zarra, 2019). Public support schemes help overcome the barriers to implementing this technology, such as a lack of skilled installers. The study concludes that with well-planned renovations paired with support schemes, heat pumps can be installed at reasonable cost.

The Netherlands' Climate Agreement targets an expansion of district-wide heating, in which a centralized source provides heating for multiple buildings using a network of insulated pipes (ten Haaft, 2020). Our findings suggest that heat pumps would also likely be a more cost-effective solution than hydrogen for district heating. However, it is difficult to draw a concrete conclusion because heating at this scale may incur lower hydrogen infrastructure costs compared to when hydrogen is used in individual single-family houses.

We estimate higher costs of using hydrogen in heating compared to the findings of a study by TNO, a Dutch research organization. That study also assesses the cost of using low-GHG hydrogen for heating in the Netherlands. They find that SMR + CCS hydrogen can be produced at just over €2 per kg in 2030. In contrast, we find that SMR + CCS hydrogen will cost around €4 per kg to produce in 2050. TNO reports that electrolysis hydrogen could be produced at €4 per kg as early as 2030, while we find that this cost could not be reached until 2050. TNO's costs are calculated based on the IEA's *Future of Hydrogen* (2019), but it is unclear how they adapted IEA's technology cost projections to the Dutch case. Regardless, it is possible that TNO assumes natural gas is used as process fuel in order to arrive at this cost, which means the GHG reduction potential of the pathway is only 42%–61% compared to using natural gas (Baldino et al., 2020). In our analysis, we assume that hydrogen, not natural gas, is used as process fuel for the SMR process, so that the GHG reduction potential increases to 69-93% compared to natural gas. This adds an additional 50 eurocents per kg to the cost of hydrogen compared to the case where natural gas is used. Christensen (2020) addresses differences between our electrolysis results and those from IEA's *Future of Hydrogen*.

Despite reporting lower hydrogen costs than our study, TNO notes that hydrogen should play a role in heating only when all-electric solutions fall short. They emphasize that electrolysis hydrogen requires a large buildup of renewable electricity coupled with electrolysis facilities and requires storage when production of electrolysis hydrogen does not align with hydrogen demand. In our assessment, we do not include long-term, seasonal storage of hydrogen, which could be a significant infrastructure requirement for electrolysis hydrogen. TNO recommends that Dutch municipalities focus on reducing energy demand in heating by improving insulation and using renewable electricity directly in heat pumps.

We also find that energy efficiency measures to reduce heat demand would be a more cost-effective strategy for achieving GHG reductions than any of the low-GHG heating pathways we assess in this study. In particular, in Baldino et al. (2020), we find that a typical UK home could reduce its heating needs by around 15% with measures to improve the building's energy efficiency that would be less expensive than the per-heat-unit cost of our heat pump scenario.

In our analyses in the UK, Germany, and the EU, which include findings similar to those in this study, we address several other studies that find lower hydrogen costs than we do. The Hydrogen Council reports a hydrogen price from reforming and CCS that is two times lower in 2030 than the prices we project for 2050 in this analysis. However, they do not explain how they determined this price, including what production pathway they assume would be used. If they assume SMR + CCS is the primary production pathway, we note that at present, SMR + CCS hydrogen only provides a greenhouse gas reduction of 42-61% compared to fossil gas. Also, the report mentions that a major benefit of hydrogen as an energy source is that it can utilize natural gas infrastructure, but it does not mention that many pipelines will need to be retrofitted, if not rebuilt, depending on the type of material they are made of and how they are operated (Dodds & Demoullin, 2013).

We also compare our UK, German and EU findings to those of two Bloomberg New Energy Finance (BNEF) reports. In our analyses, heat pumps provide a greater cost advantage than in the BNEF analysis (BNEF, 2019a, b). We explain in the UK study that the difference between our analysis and BNEF's in the cost to use hydrogen for heating may be explained by the different estimates of the cost of producing electrolysis hydrogen in Christensen (2020) and BNEF. For example, BNEF finds that electrolyzers made in China could be 50% cheaper than those manufactured in other regions, but does not provide justification.

Conclusions

It is a pivotal time for Dutch municipalities as they decide how to disconnect heating systems from natural gas by the end of 2021. We find that using a heat pump, either stand-alone or with an auxiliary hydrogen boiler, to heat a home is at least 50% less expensive than all hydrogen pathways. Fuel cells using any kind of hydrogen are the most expensive heating pathway in our analysis.

In addition, we find that SMR + CCS hydrogen cannot completely decarbonize heating. Even if zero- and low-GHG energy is used to fuel the SMR process, this pathway still releases 7-31% of the GHG emissions of fossil gas. This is because there will always be upstream natural gas leakage and carbon capture is never 100% efficient. On the other hand, the use of wind and solar power for heat pumps and electrolysis hydrogen would be fully zero-GHG.

Our findings are robust even after accounting for uncertainty over future energy prices. Natural gas and renewable electricity prices make up the majority of costs in all our scenarios, but these are difficult to predict in 2050. However, even assuming that renewable electricity prices are 50% higher than in our central assumptions, we find that heat pumps are the most cost-effective heating option in 2050. There are also uncertainties regarding the impacts that hydrogen storage will have on the gas grid, and the impact that renewable electricity will have on the electricity grid. However, it is unknown whether, or how much, these factors would affect the competitiveness of these pathways.

References

ACCESS. (2020). Housing: Types of housing. Retrieved from https://access-nl.org/housing-netherlands/housing/

American Society of Heating, Refrigeration, and Air-Conditioning Engineers. 2001. International Weather for Energy Calculations (IWEC Weather Files) Users Manual and CD-ROM. Retrieved from https://energyplus.net/weather/sources#IWEC

Astorri, S., Boorschma, A., Fernandez, M., Mitrache, R., Reberol, J., Romero, N., ..., INV WG. (2018). Ten Year Network Development Plan: Infrastructure Report. Retrieved from ENETSOG: https://www.entsog.eu/sites/default/files/2018-12/ENTSOG_TYNDP_2018_Infrastructure%20Report_web.pdf

Baldino, C., O'Malley, J., Searle, S., Zhou, Y., & Christensen, A. (2020). *Hydrogen for Heating? Decarbonization Options for Households in the United Kingdom in 2050*. Retrieved from the International Council on Clean Transportation: https://theicct.org/publications/hydrogen-heating-UK-dec2020

Baldino, C., O'Malley, J., Searle, S., & Christensen, A. (2021a). *Hydrogen for Heating? Decarbonization Options for Households in the European Union in 2050*. Retrieved from the International Council on Clean Transportation: https://theicct.org/publications/hydrogen-heating-eu-feb2021

Baldino, C., O'Malley, J., Searle, S., & Christensen, A. (2021b). *Hydrogen for Heating? Decarbonization Options for Households in Germany in 2050*. Retrieved from the International Council on Clean Transportation: https://theicct.org/publications/hydrogen-heating-germany-april2021

Bieckmann, D. (2018). Towards a Natural Gas free Amsterdam. *Urban at Parsons Blog.* https://due-parsons.github.io/methods3-fall2018/projects/towards-a-natural-gas-free-amsterdam/

Bloomberg New Energy Finance. (2019a). *Hydrogen: The Economics of Production from Renewables: Costs to Plummet*

Bloomberg New Energy Finance. (2019b). *Hydrogen: The Economics of Space and Water Heating*

CBS. (2021). *Which sectors emit greenhouse gases?* https://www.cbs.nl/nl-nl/dossier/dossier-broeikasgassen/hoofdcategorieen/welke-sectoren-stoten-broeikasgassen-uit-

Christensen, A. (2020). *Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe*. Retrieved from the International Council on Clean Transportation: https://theicct.org/publications/assessment-hydrogen-production-costs-electrolysis-united-states-and-europe

Dimitrova, A. (2020, October 28). Dutch municipalities receive another 100 milllion euros to get rid of natural gas. *The Mayor*. Retrieved from https://www.themayor.eu/en/a/view/dutch-municipalities-receive-another-100-million-euros-to-get-rid-of-natural-gas-6231

Dodds, P., Demoullin, S. (2013). Conversion of the UK gas system to transport hydrogen. *International Journal of Hydrogen Energy, 38: 18, 7189-7200*

ECN. (n.d.) *National Energy Outlook 2017*. Retrieved from https://english.rvo.nl/sites/default/files/2017/11/National%20Energy%20Outlook%202017_Summary.pdf

Eriksen, F. (2020, February 24). Netherlands highlights hydrogen cooperation with Germany. *Clean Energy Wire.* Retrieved from https://www.cleanenergywire.org/news/netherlands-highlights-hydrogen-cooperation-germany

European Commission. (2016). *EU reference scenario 2016: Energy, transport and GHG emissions, trends to 2050.* https://ec.europa.eu/energy/sites/ener/files/documents/20160713%20draft_publication_REF2016_v13.pdf

European Commission. (2020). *Eurostat: Energy statistics — supply, transformation and consumption*. Retrieved on June 15, 2020, from http://ec.europa.eu/eurostat/data/database.

Fleiter, T., Elsland, R., Herbst, A., Manz, P., Popovski, Rehfeldt, M.,..., Stabat, P. (2017). *Baseline scenario of the heating and cooling demand in buildings and industry in the 14 MSs until 2050*. Retrieved from the Heat Roadmap for the EU: https://heatroadmap.eu/wp-content/uploads/2018/11/HRE4_D3.3andD3.4.pdf

ten Haaft, M. (2020). *Anticipating the future Dutch district heating system*. https://www.accenture.com/nl-en/blogs/insights/anticipating-the-future-dutch-district-heating-system

Holland Logistics Library. (2020). *5 Reasons NL & Energy*. Retrieved from https://hollandlogisticslibrary.com/inbound/resource/5-reasons-nl-energy

Hydrogen Council. (2020). *Path to hydrogen competitiveness: A cost perspective*. https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

In de Braekt, M. and Waverijn, J. (2020, April 9). The Dutch government publishes an ambitious strategy and policy agenda on the development of the clean hydrogen market. *Lexology.* https://www.lexology.com/library/detail.aspx?g=6353afeb-a01a-42c9-b1f4-3126ff579a41

International Energy Agency. (2019). *The Future of Hydrogen*. https://www.iea.org/reports/the-future-of-hydrogen

International Energy Agency. (2020). *The Netherlands 2020: Energy Review* (Executive Summary). https://www.iea.org/reports/the-netherlands-2020#executive-summary

Klaus, T., Vollmer, C., Werner, K., Lehmann, H., & Müschen, K. (2010). *Energy target 2050: 100% renewable electricity.* Retrieved from the Umwelt Bundesamt: https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/energieziel_2050_kurz.pdf

Ministry of Economic Affairs and Climate Policy, Government of the Netherlands. (2020a). *Kamerbrief over de rol van gas in het energiesysteem van nu en in toekomst*. https://www.rijksoverheid.nl/documenten/kamerstukken/2020/03/30/kamerbrief-over-de-rol-van-gas-in-het-energiesysteem-van-nu-en-in-toekomst

Ministry of Economic Affairs and Climate Policy, Government of the Netherlands. (2020b). *Government Strategy on Hydrogen*. https://www.government.nl/documents/publications/2020/04/06/government-strategy-on-hydrogen

Moya, J., Tsiropoulous, I., Tarvydas, D., Nijs, W. (2019). *Hydrogen use in EU decarbonisation scenarios*. Retrieved from the European Commission Joint Research Centre: https://ec.europa.eu/jrc/sites/jrcsh/files/final_insights_into_hydrogen_use_public_version.pdf

Parkinson, B., Balcombe, P., Speirs, J. F., Hawkes, A.D., Hellgardt, K. (2019). Levelized costs of CO_2 mitigation from hydrogen production routes. *Energy Environ. Sci., 12, 19-40.*

Searle, S. & Christensen, C. (2018). *The decarbonization potential of electrofuels in the European Union*. Retrieved from The International Council on Clean Transportation: https://www.theicct.org/publications/decarbonization-potential-electrofuels-eu

Sia Partners. (2017). *One million Dutch households affected by energy poverty*. https://www.sia-partners.com/en/news-and-publications/from-our-experts/1-million-dutch-households-affected-energy-poverty#:~:text=Number%20of%20Dutch%20households%20living,pressing%20issue%20for%20the%20country.

Sijm, J., Beurskens, L., Marsidi, M. ,Niessinnk, R., Scheepers, M., Smekens, K., ..., de Wilde, H. *Review of energy transition scenario studies of the Netherlands up to 2050*. Retrieved from TNO: https://publications.tno.nl/publication/34636338/7YsLTC/TNO-2019-P12095.pdf

Simonelli, F., Zarra, A. (2019). *Case study on heat pumps in Arnhem, the Netherlands: Annex A.3 to Part 1 of the study on the competitiveness of the renewable energy sector*. Retrieved from the European Commission: https://www.buildup.eu/sites/default/files/content/mj0319523enn.en_.pdf.

Van het gas af: veel gemeenten worstelen met betaalbaarheid. (2020, June 30). *NU.nl*. Retrieved from https://www.nu.nl/algemeen/6061299/van-het-gas-af-veel-gemeenten-worstelen-met-betaalbaarheid.html

van t' Wout, B. (2021). *Visie op het warmtesysteem en de ontwikkeling daarvan*. https://www.tweedekamer.nl/kamerstukken/brieven_regering/detail?id=2021Z07093&did=2021D15672

Voortgangsoverleg Klimaatakkoord. (2021). *Klimaatakkoord: Afspraken van het Klimaatakkoord (Climate Agreement: Agreements of the Climate Agreement)*. https://www.klimaatakkoord.nl/klimaatakkoord.

Weeda, M. &. Niessink, R. (2020). *Waterstof als optie voor een klimaatneutrale warmtevoorziening in de bestaande bouw (Hydrogen as an option for a climate-neutral heat supply in existing buildings)*. Retrieved from TNO: https://www.tno.nl/nl/over-tno/nieuws/2020/3/waterstof-als-alternatief-voor-aardgas/