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Hydrogen for heating? Decarbonization options for households in the European Union in 2050

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

Summary

In light of the European Commission's proposal to raise the 2030 GHG reduction target to at least 55% compared to 1990 levels, policymakers are focusing on the best options for decarbonizing the energy system in Europe. In private residences, most energy demand comes from heating, highlighting the importance of decarbonizing this sector. In this study, we compare the cost of several low-greenhouse gas (GHG) or GHG-neutral residential heating technologies 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. In our assessment, we include low-carbon hydrogen from steam-methane reforming (SMR) using natural gas combined with carbon capture and storage (CCS), or SMR + CCS, and zero-carbon hydrogen produced from renewable electricity using electrolysis.

As shown in Figure ES1, we find that air-source heat pumps are the most cost-effective residential heating technology in 2050 and are at least 50% lower cost than the hydrogen-only technologies. In a sensitivity analysis, we find that even if natural gas costs were 50% lower or renewable electricity prices were 50% higher in 2050 compared to our central assumptions, heat pumps would still be more cost-effective than hydrogen boilers or fuel cells. We find that renewable electrolysis hydrogen can be cost competitive with SMR + CCS hydrogen in 2050, although electrolysis hydrogen is not produced at scale today. At the same time, we 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.

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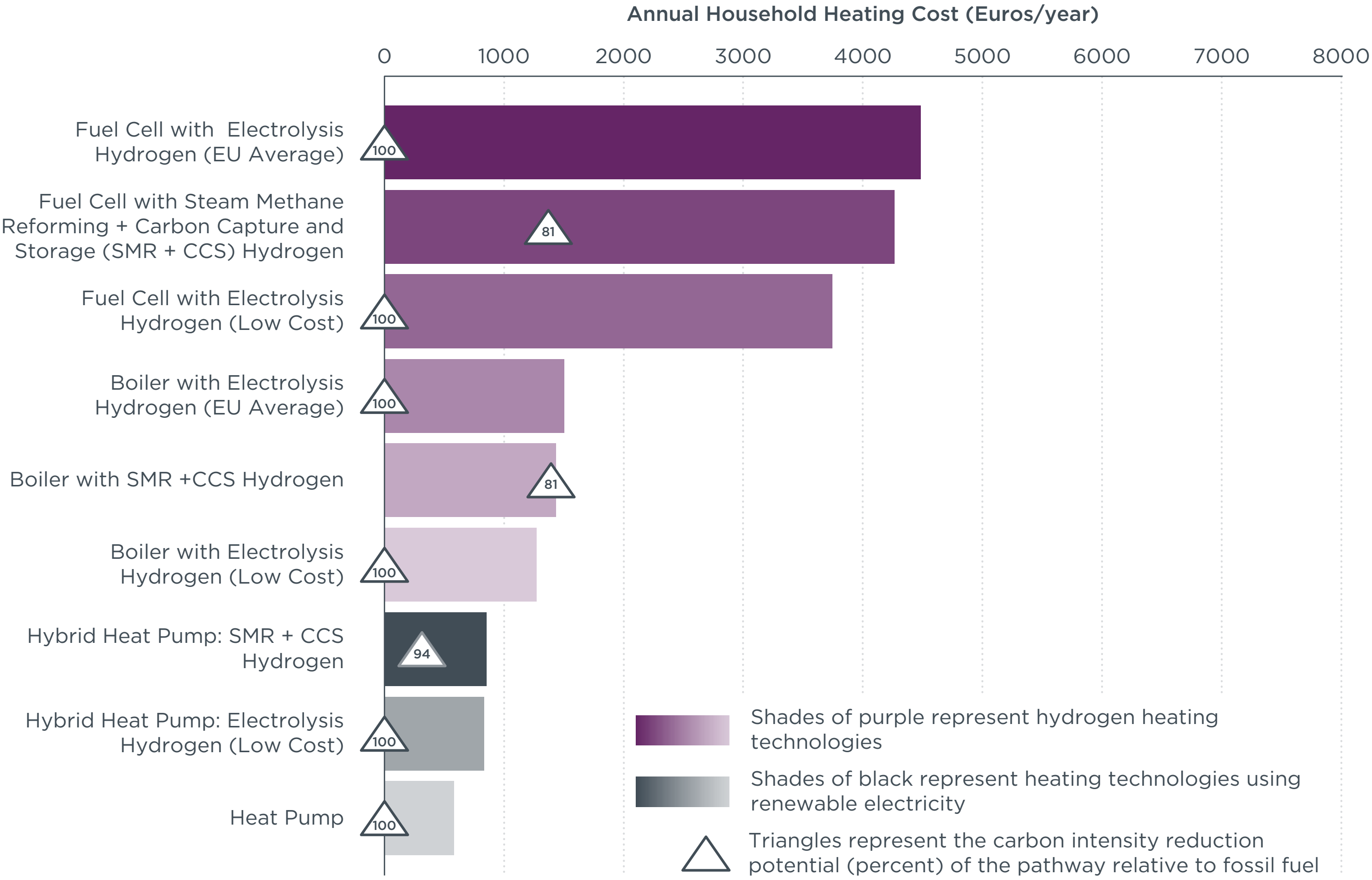
Our analysis shows that all pathways using renewable electricity have a near-zero GHG intensity, while SMR + CCS hydrogen could reduce GHG emissions by 69%–93% compared to natural gas if improvements are made in the future to reduce the GHG intensity of this pathway. Quantifying the GHG impact and cost effectiveness of various heating pathways is relevant for European policymakers facing decisions on how to both decarbonize buildings and alleviate energy poverty in line with commitments made in the Renovation Wave Initiative.



ES1. Cost comparison and greenhouse gas intensity reduction potential of different technology options for heating a household for one year in the EU in 2050.

Introduction

The European Commission's proposal to raise the 2030 GHG reduction target to at least 55% compared to 1990 levels will require a drastic transition away from fossil energy sources in Europe (European Commission, 2020b). The building sector is responsible for 40% of the final energy consumption in Europe and 36% of the European Union's (EU) greenhouse gas (GHG) emissions (McPhie & Crespo Parrondo, 2020). Buildings are thus an important component for greenhouse gas reduction in the European economy. In residences, heating makes up 64% of energy consumption, and fossil fuels, mainly gas, help meet a large portion of this demand (European Commission, 2019). At the same time, about 34 million Europeans are unable to properly warm their homes, and the EU has committed to tackle energy poverty as a part of its 2020 Renovation Wave initiative (European Commission, 2021).

This study provides evidence on what decarbonized heating technology would be most cost-effective for households and its findings are hence relevant for European policymakers facing decisions on how to decarbonize buildings at lowest costs for consumers. Improving insulation can play a role in reducing heating demands, but to achieve ambitious climate goals laid out in the European Green Deal by 2050, a transformation of the energy sources used in heating will be necessary. Possible decarbonization options for the heating sector include hydrogen, renewable electricity, or a combination of the two.

This study assesses the cost of heating single family homes, which make up around a third of houses in the EU (Eurostat, 2020). When heating these kinds of homes using decarbonized energy in 2050, we assume that the two most likely technologies using hydrogen are either a hydrogen boiler or fuel cells, since they are the most commercially mature. Heat pumps are another mature technology and can utilize renewable electricity directly for heating at effective efficiencies of 250% to 400%, which exceeds 100% due to the fact that they transfer, as opposed to generate, the heat (Moya, Tsiropoulous, Tarvydas, & Nijs, 2019).

This study draws upon the methodology and assessment developed by Baldino, O'Malley, Searle, Zhou, and Christensen (2020). It assesses the annual cost of space heating in a typical single-family home in the EU in the year 2050 using low-carbon hydrogen, renewable electricity, or a mixture of both energy sources. It complements our other study addressing the same question in the United Kingdom (Baldino et al., 2020), and upcoming studies assessing the Netherlands and Germany. We assess two scenarios using hydrogen, one where the home is heated solely by a boiler, either using hydrogen produced from steam methane reforming and carbon capture and storage (SMR + CCS) or electrolysis hydrogen from renewable electricity, and another using a fuel cell and an auxiliary hydrogen boiler for cold spells. As for using renewable electricity to heat homes in 2050, we assess two scenarios using a heat pump. In both, we assume wind or solar energy is used. In one of these scenarios, we assume the home is heated solely by the heat pump due to increasing global temperatures. The other scenario includes an auxiliary hydrogen boiler to supplement the heat pump on cold weather days. We also assess the lifecycle GHG impacts of all of these heating pathways.

Methodology

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

Hydrogen production costs

We assume that all hydrogen from natural gas will be produced in the EU and that SMR plus carbon capture and storage will be the primary technology used to produce this hydrogen in the 2050 timeframe. We follow the same methodology for calculating SMR + CCS hydrogen production cost as detailed in Baldino et al. (2020). The natural gas price is a major component of the overall cost of producing SMR + CCS hydrogen. We use a projected price of natural gas in the EU in 2050 from Duic, Stafanic, Lulic, Krajacic, Puksec, and Novosel (2017).

A recent ICCT study (Christensen, 2020) based the production cost for electrolysis hydrogen in European countries on wind and solar capacity factors from a European Commission Joint Research Centre (JRC) study. For this assessment, the JRC provided updated solar and wind capacity factors, which we use to adjust the cost of the electrolysis hydrogen (F. Monforti- Ferrario, personal communication, December 15, 2020). We assume electrolyzers are either grid connected or directly connected to a renewable electricity generator, whatever is more economical for that member state (Christensen, 2020). We find that one of the lowest-cost locations for electrolysis hydrogen production within the EU in 2050 will be in Sweden. In this analysis, we consider two cases: one using the hydrogen production cost for Sweden and the other using a weighted average of costs across all EU member states based on current electricity consumption. It seems likely that countries where there is the lowest cost of hydrogen production, such as Sweden, will not have the capacity to produce all of the EU's electrolysis hydrogen. Nevertheless, we may still consider the heating pathways using this price for electrolysis hydrogen as an illustration of a scenario where electrolysis hydrogen is able to be utilized at its lowest cost of production.

Hydrogen transport

Hydrogen could be transported to households either by pipeline or by truck. Generally, transporting fuels by pipeline is more economical when demand is high. We assume this would be the case if hydrogen were used universally in boilers or fuel cells within the EU. In these scenarios, we assume that hydrogen could be transported using a network similar to today's natural gas pipeline at approximately the same capacity. Existing natural gas pipelines would generally need to be retrofitted or rebuilt, depending on the material, to be compatible with hydrogen. We thus assess the cost of retrofitting the EU's current natural gas pipeline network, following our methodology in Baldino et al. (2020). We take the current transmission natural gas pipeline length from Astorri et al. (2018) and distribution pipeline length from Marcogaz (2018). In order to levelize the cost of pipeline retrofitting per kg of hydrogen supplied, we assume 2050 hydrogen demand will be the same as we would currently expect for natural gas in 2050 in a business-as-usual scenario with no policies to promote a transition from natural gas to hydrogen. For this, we use the EU Reference Scenario projection for total natural gas demand in the EU in 2050 (European Commission, 2016). We amortize the total pipeline retrofitting cost by 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 large industrial users) natural gas prices, using an average of this term in the UK and Netherlands due to data availability for these countries (Baldino et al., 2020; ECN, n.d.; European Commission, 2020a).

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 calculate the cost to ship liquid hydrogen, we assume an average of the distances from major ports to population hubs in Netherlands and Germany (250 km). Though this is a simplification of the trucking distances that we can expect in each EU member state, the biggest part of the trucking fee is due to liquefaction so the distance does not significantly affect the final cost of heating (Yang & Ogden, 2007). We report a sensitivity analysis of the impact of the trucking distance on final heating cost in Baldino et al. (2020).

Residential heating technology and cost

We assess four heating scenarios for heating single family houses in the EU: 1) boiler using hydrogen; 2) fuel cell using hydrogen, plus an auxiliary hydrogen boiler for cold spells; 3) heat pump using 100% renewable electricity to meet all heating demand; and 4) hybrid heat pump with an auxiliary hydrogen boiler for cold spells, in case the heat pump alone cannot meet all of the demand.

We estimate household space heating demand in 2050 using an average of household heating demand for 14 member states from 2015, which represented 90% of the total demand for heating and cooling in the EU-28 (Fleiter et al., 2017). We multiply this estimate of 2015 residential space heating demand by the expected 25% reduction in demand between 2015 and 2050 across the 14 member states included in the Fleiter et al. study to estimate what demand will be in 2050.

We conduct an analysis of daily average temperatures to determine the time that an auxiliary hydrogen boiler would be needed to supplement either a heat pump or fuel cells. We use typical meteorological year (TMY) data in central France, which is close to the geographic population center of Europe, from 1983 to 1999 (American Society of Heating, Refrigeration, and Air-Conditioning Engineers ASHRAE, 2001). We calculate that a heat pump or fuel cell could be used to meet 69% of the heating needs in a year in France, and the remainder of the time, an auxiliary boiler would be needed. We do not incorporate heat storage in our analysis.

In a fuel cell, hydrogen and oxygen are combined in an electrochemical reaction, which generates primarily electricity but also heat and water as byproducts. We assume that this electricity would be used to supply the electricity needs of that residence, and that the excess will be sold to electricity utility companies. We derive electricity demand for residences in 2050 from Klaus, Vollmer, Werner, Lehmann, and Müschen (2010), assuming that heating demand in German residences is representative of the typical residence in the EU. We assume that excess electricity production would be sold to utility companies at the average wholesale price for renewable electricity in the EU in 2050 based on the 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 EU in 2050. This is illustrated in Figure 1, where the bars compare the annual cost of the different options in the EU in 2050. These costs include annuitized capital expenses, operating expenses, and fuel costs. The heat pump-only scenario is 60% lower cost than the scenario with a boiler using SMR + CCS hydrogen and about 50% lower cost than using a boiler with low-cost electrolysis hydrogen from Sweden. The hybrid heat pump scenarios are 30%–40% less expensive than using hydrogen boilers, depending on the source of the hydrogen used in each. Low-cost electrolysis hydrogen from Sweden is less expensive than SMR + CCS hydrogen, and the EU-average cost for electrolysis hydrogen is slightly more expensive than SMR + CCS hydrogen. These differences in production costs lead to the corresponding difference in the relative expense of each of the pathways using hydrogen. All fuel cell scenarios are around three times more expensive as using a hydrogen boiler. We find that a fuel cell using SMR + CCS hydrogen is seven times more expensive than using a heat pump alone with renewable electricity.

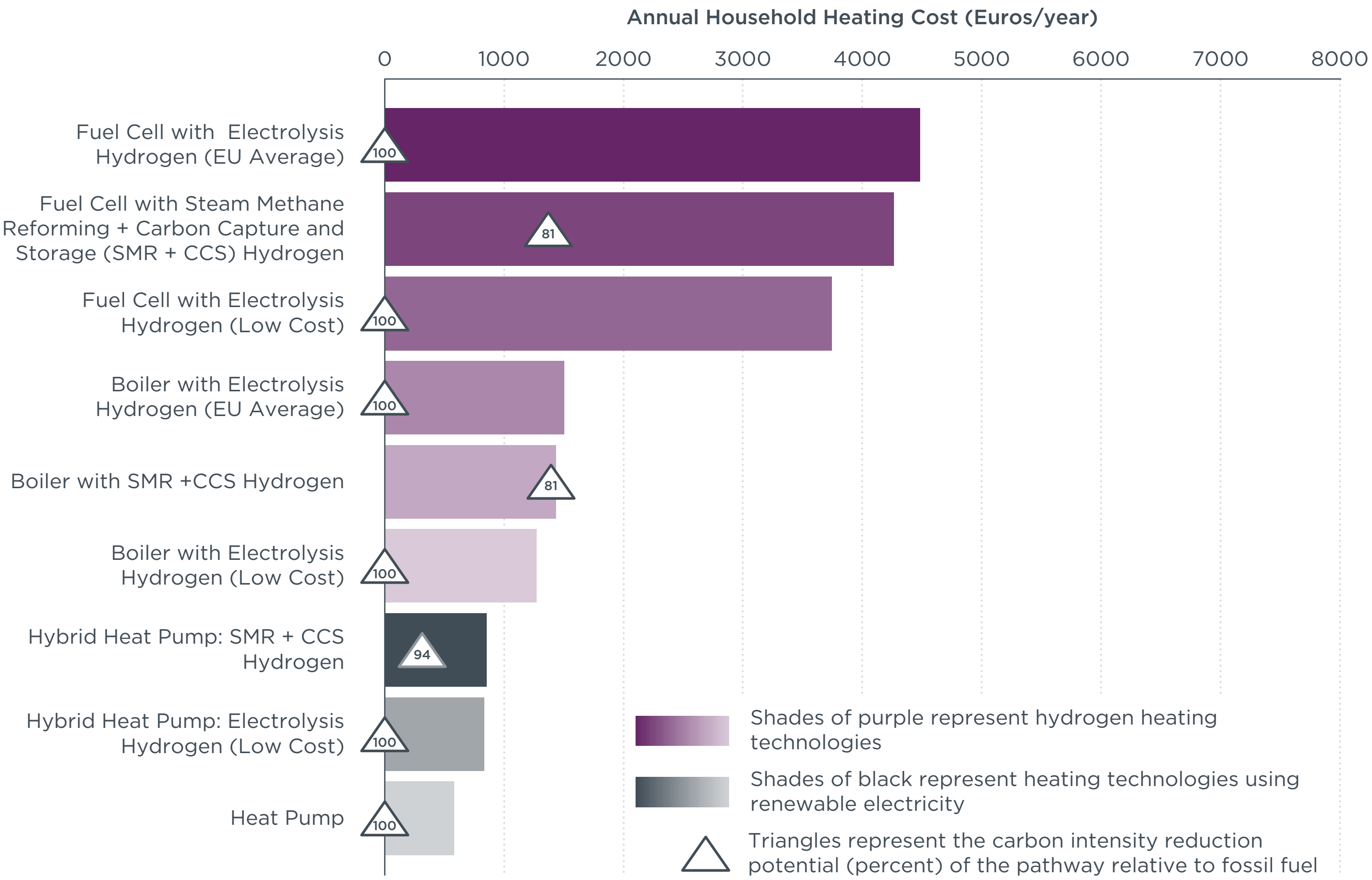


Figure 1. Cost comparison and greenhouse gas intensity reduction potential of different technology options for heating a household for one year in the EU in 2050.

The GHG intensity, or the total GHG impact per unit of energy delivered, of each pathway is also illustrated in the symbols in Figure 1. All pathways based on renewable electricity from wind and solar are zero-carbon, while the pathways using SMR + CCS hydrogen have a GHG intensity of 5 gCO_2e/MJ to 22 gCO_2e/MJ, which corresponds to a greenhouse gas reduction of 69%–93% compared to natural gas (represented as an average greenhouse gas reduction of 81% in Figure 1). At present, however, SMR + CCS hydrogen only provides a greenhouse gas reduction of 42%–61% compared to natural gas, assuming a GHG intensity of 72 g CO_2e/MJ for natural gas (Giuntoli, Agostini, Edwards, & Marelli, 2017). The range of carbon intensity reductions relative to natural gas shown in Figure 1 reflects upstream leakage rates during natural gas production and transport of 0.5%–2%, as well as a carbon capture efficiencies between 70% and 90% (Parkinson, 2019). For the hybrid heat pump pathway, the GHG intensity is a weighted average of that of renewable electricity and SMR + CCS hydrogen, based on the percent of the year that the auxiliary hydrogen boiler would need to be used. Baldino et al. (2020) explains how we derive these carbon 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). The energy costs for the fuel cell pathway are net of the revenue from selling excess electricity to the grid. The input energy (hydrogen or renewable electricity) accounts for the majority of overall cost for each pathway. For the heating pathway using a hydrogen boiler, OPEX is larger than CAPEX because hydrogen boilers are relatively inexpensive but require annual maintenance. For the other pathways, CAPEX represents the second-largest cost component. Household-scale fuel cells are not a cost-effective electricity generation pathway, so while fuel cells receive a reduction in energy costs because of the excess electricity they produce, the reduction is not great enough to make the fuel cell cost competitive with the other pathways.

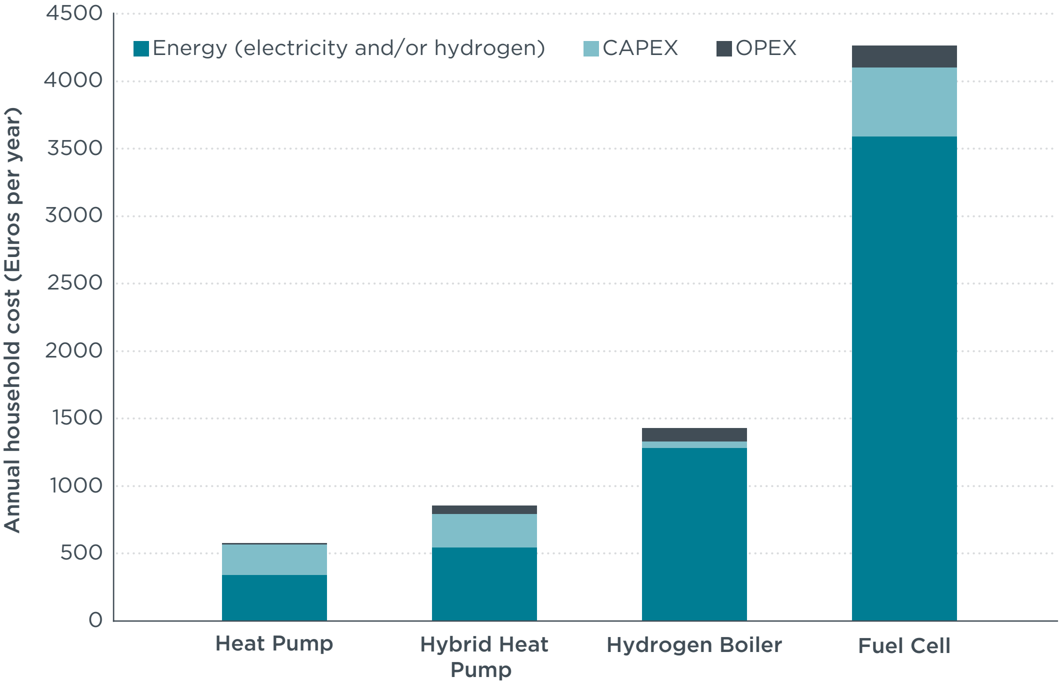


Figure 2. Cost components of heating pathways. The cost of energy for the fuel cell scenario is net of excess electricity generation that is sold to the grid. For the pathways using hydrogen, the hydrogen is assumed to be produced by steam methane reforming with carbon capture and storage.

Figure 2 shows that the cost of input energy, in the form of hydrogen or renewable electricity, makes up the majority of the cost for each of the different pathways in our analysis. But the cost of energy in 2050 is difficult to predict. Figure 3 presents our sensitivity analysis showing how changing energy prices would affect our results. For all scenarios except fuel cells using SMR + CCS hydrogen, the lower and upper bounds of the error bars represent a 50% decrease and increase, respectively, in all energy-related costs. This changes the total cost of these scenarios by 20%–30%. Unlike in the other scenarios, changes in input renewable electricity and natural gas costs augment, rather than counteract, each other in our fuel cells using SMR + CCS hydrogen scenario. The lower bar represents a case where renewable electricity prices are 50% higher (providing more revenue when the electricity is sold back to the grid compared to the main scenario) and natural gas prices are 50% lower, and the upper bar represents the opposite. In this case, the sensitivity analysis revealed a larger range, with total costs varying by 40%.

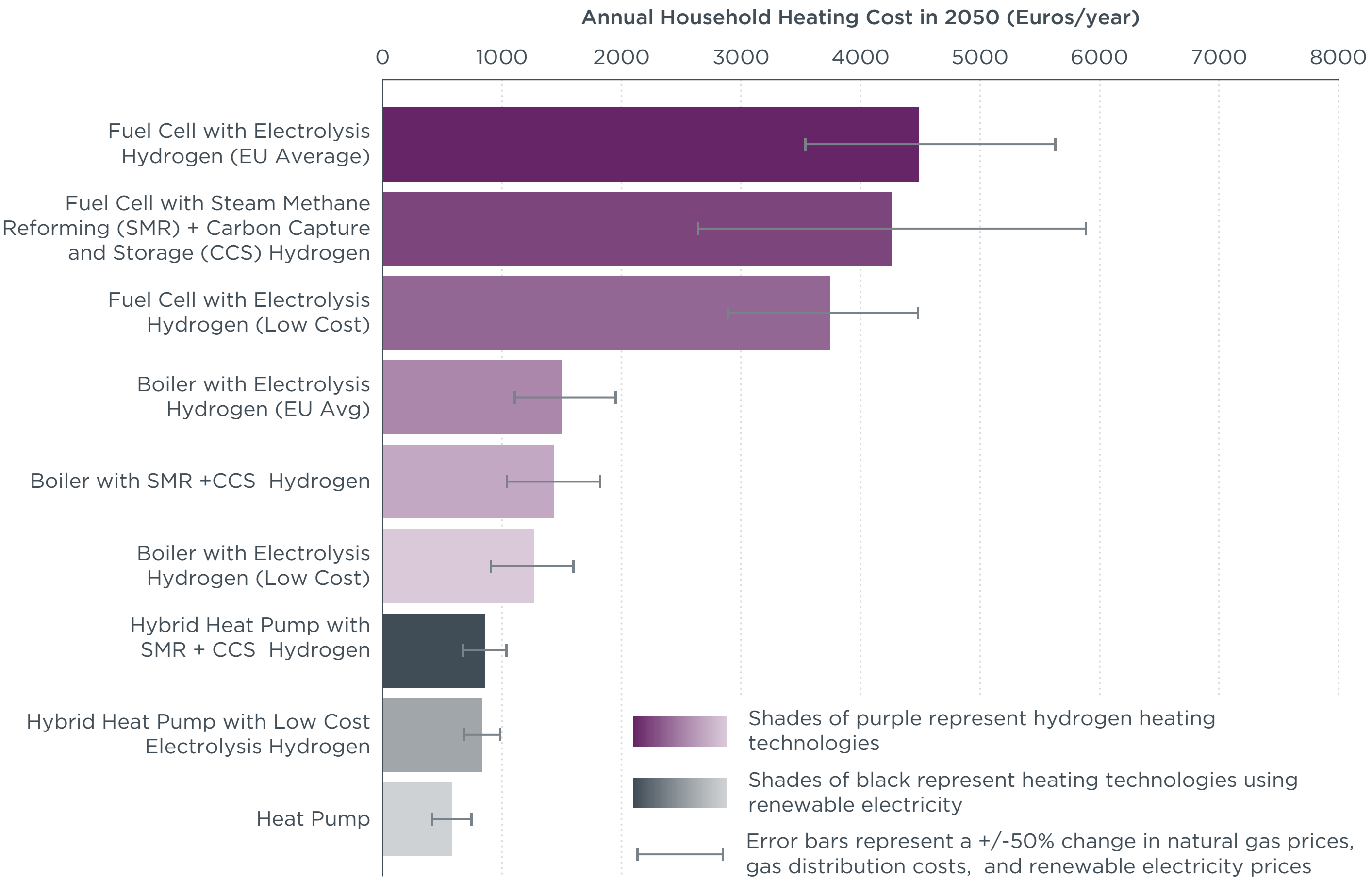


Figure 3. Sensitivity analysis on the cost of household heating.

All heat pump scenarios would remain the most cost-effective option even if renewable electricity prices were 50% higher and natural gas prices and gas distribution costs were 50% lower than we assume. We find that the cost advantage of heat pumps would increase were natural gas prices and gas distribution fees 50% higher, or renewable electricity prices 50% lower, in 2050 than our central assumption. Even with a 50% change in energy prices, none of the fuel cell scenarios become cost competitive with the other pathways.

Discussion

Out of the low-GHG heating options that we assess, we find that it will be most cost effective for a single-family home in the EU in 2050 to use a heat pump, with or without an auxiliary boiler for cold days. We find that hydrogen boilers are more expensive than heat pumps and that fuel cells are more expensive than the other options. The cost of hydrogen depends on the production method used. The least expensive type of hydrogen in our analysis is electrolysis hydrogen produced in Sweden and exported to other EU countries. However, depending on future demand for hydrogen, it is possible that Sweden and other countries producing electrolysis hydrogen at the lowest cost would be unable to supply hydrogen for the entire EU. Hydrogen produced by SMR + CCS is more expensive than Swedish electrolysis hydrogen, and the average cost of hydrogen produced across EU member states is slightly higher than for SMR + CCS hydrogen.

Hydrogen produced from SMR + CCS can provide a 69%-93% reduction compared to natural gas, while heat pumps and electrolysis hydrogen pathways use zero carbon energy inputs and provide high GHG savings with greater certainty. The reduction for

SMR + CCS hydrogen assumes that renewable electricity and some of the hydrogen is used to fuel the SMR process.

Some stakeholders, such as Agora Energiewende, support a reliance on heat pumps running on renewable electricity to achieve decarbonization and the use of electrolysis-based hydrogen only in the sectors where electrification is difficult (Buck, Graf, and Graichen, 2019). They emphasize that in the near-term prior to 2030, efficiency measures will play the most important role in reducing the climate impact from heat, which they discuss in detail in a report by the Institut für Energie und Umweltforschung, Fraunhofer IEE, and Consentec (2018). In Baldino et al. (2020) we 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. Fraunhofer IEE, in a study commissioned by the Information Center for Heat Pumps and Cooling Technology (IZW), also provides a broad overview of research on hydrogen and heat pumps and concludes that heat pumps will ease demand for hydrogen, which they find to be minimally available at low-cost (Gerhardt et al., 2020). They find that electricity grid infrastructure does not represent a significant obstacle to using heat pumps.

The Hydrogen Council, on the other hand, claims that hydrogen solutions will be some of the most cost-effective ways to support the heating sector's transition to low-carbon energy in 2030, but it should be noted that they do not identify which hydrogen production pathway they assume (Hydrogen Council, 2020). It is likely they assume SMR + CCS hydrogen is used for the hydrogen pathways, since they write that electrolysis hydrogen will not reach cost competitiveness until 2030. In this case, it is important to note that, at present, SMR + CCS hydrogen only provides a greenhouse gas reduction of 42%–61% compared to natural gas. The Hydrogen Council may also consider autothermal reforming, which is not yet commercially mature but can offer greater GHG savings due to the potential for higher capture efficiency with this pathway. Heat pumps that utilize zero-carbon energy such as wind or solar can provide nearly complete decarbonization.

In addition, the Hydrogen Council reports that, in Europe, hydrogen from reforming and CCS could be produced at prices 2.5 times lower in 2030 than the prices we project for 2050. They do not explain how they arrived at this hydrogen price; in particular, they do not specify whether they assumed steam methane reforming or autothermal reforming, a less mature technology that uses oxygen instead of steam to produce hydrogen, when arriving at these prices. Further, they emphasize that hydrogen is an attractive energy source because existing natural gas infrastructure can be utilized, but fail to 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). The Hydrogen Council notes in their comparison of heating pathways that heat pumps could provide a cost advantage depending on hydrogen infrastructure needs.

The industry-led Gas for Climate report presents a vision for heating Europe in 2050 where 37% of buildings are still connected to the gas grid and utilize a hybrid heating system (Peters et al., 2020). However, it's unlikely that demand for gas will be high enough to justify the continued use of gas infrastructure. Our research suggests, in some cases, it may be less expensive to transfer hydrogen by truck than to retrofit existing gas infrastructure. Additionally, Gas for Climate reports that biomethane will be the primary gas used in these hybrid systems. As that study highlights, for biomethane to help achieve decarbonization in any sector, the feedstock should be made from sustainable, low-carbon materials such as waste and residues that do not have current uses (Peters et al., 2020; Baldino, Pavlenko & Searle, 2018a). Our previous research shows that the amount of biomethane available from these feedstocks in the EU is very low and will not be available in the volumes that Gas for Climate advocates for in their 2050 heating scenario (Baldino, Pavlenko & Searle, 2018b). Additionally, as we illustrate in the analysis of heating pathways in the UK in 2050, biomethane is a more expensive resource to use than both SMR + CCS or electrolysis hydrogen (Baldino et al., 2020). Finally, it is possible that with increased efficiency improvements, as well as expected temperature increases with climate change, it may be possible to use heat pumps without auxiliary hydrogen boilers in many EU countries.

Our findings in Baldino et al. (2020) on the cost of heating in the UK in 2050 are similar to the findings presented here. Our analysis suggests that using district-wide heat pumps, where a single heat pump would provide heating for multiple buildings using a network of insulated pipes, could be more cost-effective than using hydrogen, but it is difficult to draw a concrete conclusion because heating at this scale may incur lower hydrogen infrastructure costs. In the UK paper, we also discuss the cost of efficiency improvements compared to the cost of heating a home with hydrogen or renewable electricity. Using data from Connolly, Hansen, and Drysdale (2015), we find that a typical UK home could reduce its heating needs by around 15% with measures that would be less expensive than the per-heat-unit cost of our heat pump scenario. In addition, the UK study does not consider long-term, seasonal storage of hydrogen, which could be a significant issue, particularly for electrolysis hydrogen produced using wind and solar electricity.

We also compare our findings to those of two Bloomberg New Energy Finance (BNEF) reports. In the UK study, we find that although BNEF also finds heat pumps to provide a cost advantage compared to hydrogen boilers using electrolysis hydrogen in 2050, we find heat pumps have a greater cost advantage (BNEF, 2019a; BNEF, 2019b). A major reason for the difference in the cost to use hydrogen for heating between our study and BNEF's is possibly due to differences between Christensen (2020) and BNEF regarding the cost to produce electrolysis hydrogen. For example, BNEF (2019a) assumes that electrolyzers made in China could be 50% cheaper than those manufactured in other regions without providing justification.

Conclusions

Not all options to decarbonize the buildings sector, particularly heating, have equal carbon reduction potential. SMR + CCS hydrogen cannot completely decarbonize heating because there will always be upstream natural gas leakage and carbon capture is never 100% efficient. Even in a scenario where zero- and low-carbon energy is used to fuel the SMR process, this pathway still releases 7%–31% of the GHG emissions of natural gas. In contrast, the use of wind and solar power for heat pumps and electrolysis hydrogen would be fully zero-carbon.

At the same time, it is important to consider how end users will be impacted by climate policy, especially in light of the fact that many Europeans already struggle with energy poverty. We find that using a heat pump to heat a home is at least 50% lower cost than all hydrogen scenarios. A hybrid heat pump using a limited amount of low-cost electrolysis hydrogen from Sweden in the auxiliary boiler is the second most cost-effective heating pathway in our analysis, being 30%–40% less expensive than using a hydrogen boiler. Fuel cells using any kind of hydrogen are the most expensive heating pathway in our analysis.

There are several important factors of uncertainty in our analysis. The first is related to natural gas and renewable electricity prices, which make up the majority of costs in all our scenarios. Even if we increase renewable electricity prices by 50% compared to our central assumptions, we still find that heat pumps the most cost-effective heating option in 2050. Further, there are 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.

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