WORKING PAPER 2021-16

APRIL 2021

Hydrogen for heating? Decarbonization options for households in Germany 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

By 2030, the German government aims to reduce greenhouse gas (GHG) emissions from the buildings sector by two-thirds relative to 1990 levels. The heating sector will be an important part of this goal; in German residences, about 60% of final energy demand goes to space heating, and two-thirds of space heating is met with fossil fuels. There are multiple GHG-reduction options available to the heating sector, and the German government will need to determine which options to promote, especially in light of the fact that 17% of German households spend a high share of their income on energy costs. In this study, we assess several low-GHG or GHG-neutral residential heating pathways in Germany to determine which will be the most cost competitive in 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 zero-carbon hydrogen produced from renewable electricity using electrolysis as well as low-GHG hydrogen from steam-methane reforming (SMR) using natural gas combined with carbon capture and storage (CCS), or SMR + CCS.

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 40% lower cost than the hydrogen-only technologies. We find that when we perform a sensitivity analysis, 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 were electrolysis hydrogen to be imported from other parts of Europe it could be cost competitive with SMR + CCS hydrogen produced in Germany in 2050, although electrolysis hydrogen is not produced at scale today. Compared to all of the low-GHG heating pathways we assess in this study, energy efficiency measures to reduce heat demand would be a more

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Acknowledgements: This report has been supported by the European Climate Foundation. The authors are responsible for the information and views set out in this report. The European Climate Foundation cannot be held responsible for any use which may be made of the information contained or expressed therein. Thanks to Peter Mock, Stijn Carton, Femke de Jong, Eleonora Moschini and Kaliana French for their review.

cost-effective strategy for achieving GHG reductions. Our analysis shows that all pathways using renewable electricity have a near-zero GHG intensity, while 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. Our findings are relevant for German policymakers deciding how to both decarbonize heating and alleviate energy poverty.

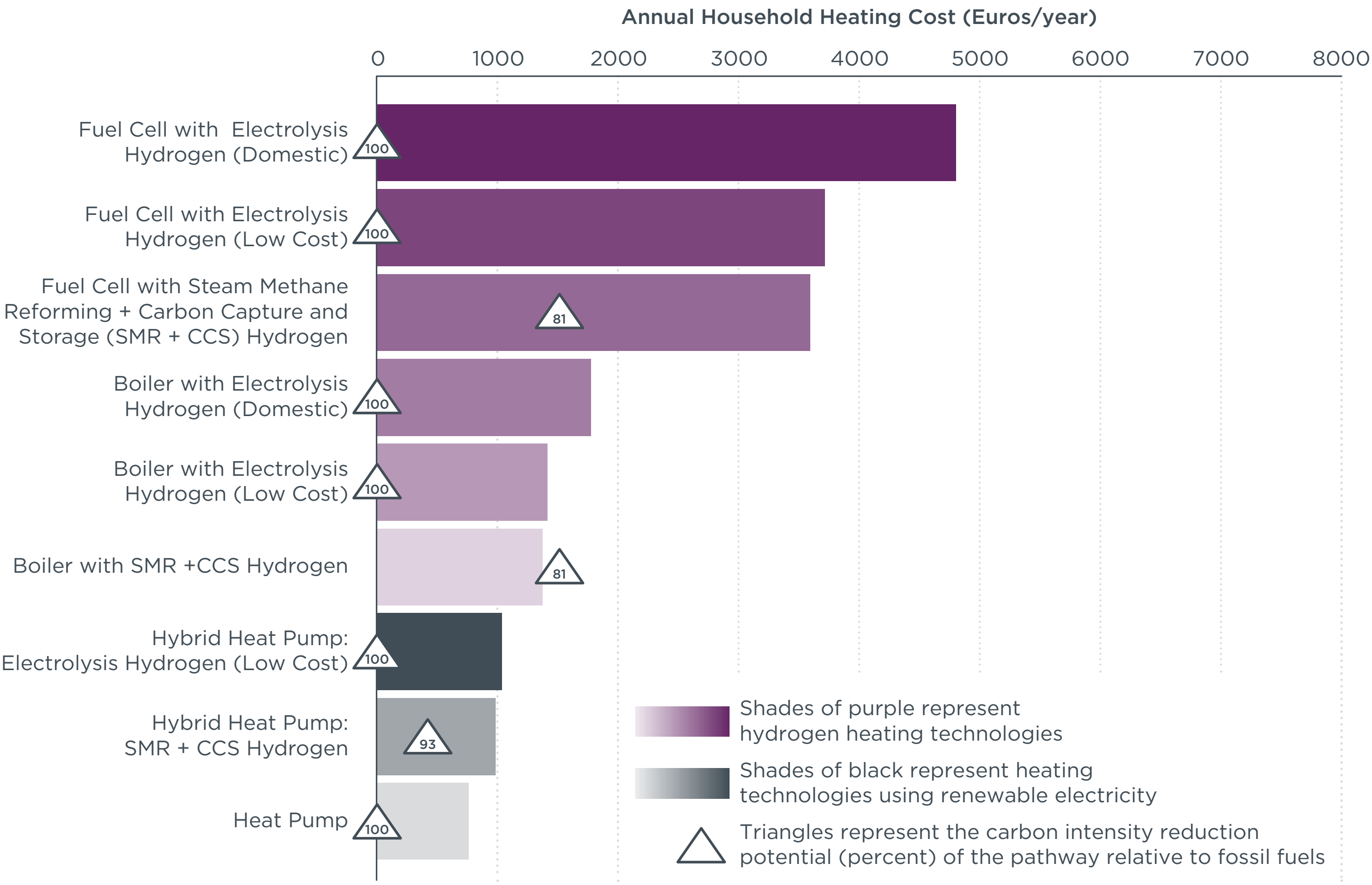

Figure ES1. Cost comparison (in euros) and greenhouse gas intensity reduction potential of different technology options for heating a household for one year in Germany in 2050.

Introduction

The German federal government has the ambitious goal to decarbonize the country by 2050, which means all sectors must come close to decarbonizing over the next decades (German Federal Government, 2021). Currently, Germany has the highest energy demand for heating and cooling in the EU (in absolute terms), and in German residences, about two-thirds of space heating demand is met with fossil fuels (UBA, 2020). At the same time, according to the EU Energy Poverty Observatory, 17% of German households spend a high proportion of their income on energy, and 3% of people are unable to properly heat their homes (2020).

By 2030, the German government aims to reduce greenhouse gas (GHG) emissions from the buildings sector by two-thirds relative to 1990 levels (BMUB, 2021). To reduce heating demand, improving energy efficiency in buildings plays an important role, but to achieve the drastic reductions in GHG emissions in line with the government's goal, changes in the energy sources used to heat homes will be needed. Some energy stakeholder groups such as Agora Energiewende support a reliance on heat pumps running on renewable electricity to achieve decarbonization. Heat pumps are a mature technology and can utilize renewable electricity directly at efficiencies of 250% to

400%, which exceed 100% because they transfer heat rather than generate it (Moya, Tsiropoulous, Tarvydas, & Nijs, 2019). They support the use of electrolysis-based hydrogen only in the sectors where electrification is difficult (Buck, Graf, and Graichen, 2019). On the other hand, some advocates, such as the Hydrogen Council, support a strong reliance on decarbonized gases, such as hydrogen, to achieve decarbonization in the heating sector. In addition, in 2020, the German government released a Hydrogen Strategy, which includes efforts to bring hydrogen to the heating sector. One way to produce low-GHG hydrogen is to use a carbon-removal process such as steam-methane reforming (SMR) on natural gas, combined with carbon capture and storage (CCS). There is also the potential to produce zero-carbon hydrogen from electrolysis using renewable electricity.

With national greenhouse gas reduction goals in mind, an important question facing the German government is which low-GHG and GHG-neutral heating pathways to support now with an eye to global competitiveness in 2050. This study complements similar analyses in the United Kingdom and European Union, as well as an upcoming study in the Netherlands, and draws upon the methodology and assessment developed by Baldino, O'Malley, Searle, Zhou and Christensen (2020). This study focuses on single family homes for our cost analysis, as 60% of residential buildings in Germany house only one or two families (Hebling et al., 2019). We assess four heating scenarios for heating single family houses in Germany: 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. We discuss the lifecycle GHG impacts of all of these heating pathways below.

Methodology

To determine the costs and GHG intensity of each heating pathway, we utilize the same methodology and assumptions as Baldino et al. (2020), except for the differences identified here.

Hydrogen production costs

We assess SMR+CCS hydrogen and renewable electrolysis hydrogen for the 2050 timeframe, following the same methodology for calculating SMR+CCS hydrogen production cost as detailed in Baldino et al. (2020). At present, 97% of natural gas is imported in Germany, with the majority coming from Russia, the Netherlands, and Norway (U.S. Energy Information Administration, 2020). Given that Norway is a global leader in SMR + CCS hydrogen production and already exports gas to Germany, we assume that all SMR + CCS hydrogen will be imported from Norway in 2050 (Westphal, Dröge, and Geden, 2020). The natural gas price is a major component of the overall cost of producing SMR+CCS hydrogen. To estimate the price of natural gas in Norway in 2050, we take the 2019 Norwegian internal transfer natural gas price (wholesale) from Equinor and apply a projected price increase to 2050 from our UK study (Equinor, 2020; Baldino et al., 2020). We add an estimate of gas distribution fees, taxes, and marketing margin based on the average difference between wholesale and retail gas prices (for large industrial consumers) that we calculated for our analyses in the UK and Netherlands (Baldino et al., 2020; ECN, n.d; European Commission, 2020).

A recent ICCT study (Christensen, 2020) provided the production cost for renewable hydrogen from electrolysis in European countries, which is based on wind and solar capacity factors from a study from the European Commission's Joint Research Centre. For this assessment, we received updated 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). We also find that one of the lowest-cost locations for electrolysis hydrogen production within the European Union will be in Sweden, so we include hydrogen heating pathways using this hydrogen price as well. The heating pathways using this price for electrolysis hydrogen can be considered illustrative of a scenario where electrolysis hydrogen is imported from another EU country that can produce it a lower cost than Germany.

Hydrogen transport

Generally, transporting fuels by pipeline is more economical when demand is high compared to when demand is low. We assume this would be the case if hydrogen were used universally in boilers or fuel cells in Germany. For these heating scenarios, we assume that hydrogen could be transported in approximately the same amounts using a network similar to today's natural gas pipeline. Existing natural gas pipelines would generally need to be retrofitted or rebuilt depending on the material to be compatible with hydrogen. At present, there is a pipeline connecting Kårstø, Norway and Dornum, Germany (Europipe II), which opened in 1999 (Norwegian Government, n.d). We assume that this pipeline is hydrogen-ready, with no need for retrofits, given that underwater pipelines constructed in the 1990's are usually built with hydrogen-compatible materials (Oil and Gas Technology Centre, n.d.). For Germany's pipelines, we assess the cost to retrofit and construct the current natural gas pipeline network following our methodology in Baldino et al. (2020). We take the current total transmission pipeline length from Astorri et al. (2018) and current distribution pipeline length from Gasunie (n.d.). We include a planned expansion of transmission lines of 810 km (Federal Ministry for Economic Affairs and Energy, 2020).

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 and reference the EU Reference Scenario projection for this value (European Commission, 2016). We amortize the total pipeline retrofitting cost by 30 years to levelize the cost of pipeline retrofitting per kg hydrogen supplied in 2050. We expect that utility companies and pipeline operators would charge a fee to hydrogen consumers for the use of pipelines and assume that this fee would be the same as present-day gas distribution fees for natural gas in Germany. We estimate this fee as the difference between wholesale and retail (for residential users) natural gas prices, using Eurostat (European Commission, 2020) and the International Gas Union (2018).

In the scenarios where auxiliary hydrogen boilers supplement heat pumps, we expect that total hydrogen demand will be lower than the hydrogen-only scenarios and so assume that hydrogen is transported by tanker across the North Sea from Norway and then by truck for transport within Germany. We assume the same liquefaction fee as in Baldino et al. (2020) in calculating the cost of shipping liquid hydrogen across the North Sea. We use a calculator from sea-distances.org and assume a speed of 19 knots, which is a typical speed for liquefied natural gas (LNG) shipments according to Rogers (2018), to calculate the number of days the shipment would take from Kristiansund, Norway to Hamburg, Germany. Kristiansund is one of the closest ports to Equinor's Tjeldbergodden facility, where they expect to have a hydrogen liquefaction facility by 2025 (Norwegian Centres of Expertise Maritime CleanTech, n.d.). We assume one day for on-boarding and one day for off-loading the liquid hydrogen and include the number of days necessary for a return trip, since there would likely not be any return cargo in such a shipment (Rogers, 2018). We retrieve the capacity of a tanker for liquified hydrogen, as well as port fees, insurance, brokers' fees and a daily charter fee, from Rogers (2018). We multiply the charter fee assessed for LNG by 125% given that hydrogen needs to be kept at a colder temperature than LNG (Krewitt and Schmid, 2005). We also calculate how much hydrogen would be "boiled off," i.e., used as fuel for the tanker, following Rogers (2018) and Krewitt and Schmid (2005).

We assume the trucking distance in Germany to be 415 km, which is the distance from the German coast to Spangenburg, Germany, the geographic center of Germany weighted by population. Though this is a simplification of the trucking distances that can be expected in a country as large as Germany, the biggest part of the shipping cost is due to liquefaction, so this distance does not greatly 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).

As for the cost of transporting low-cost electrolysis hydrogen from Sweden to Germany, we assume that Sweden will be able to export hydrogen via existing pipelines or pipelines that are already under construction, so we do not include any additional costs. The Baltic Pipeline, expected to be completed in 2022, will provide Sweden with Norwegian natural gas and originates at the Euro II Pipeline connecting Norway to Germany (NS Energy, n.d). It is therefore possible that this existing system could be used to transport electrolysis hydrogen from Sweden to Germany in 2050.

Outside of our main heating scenarios using electrolysis hydrogen, we consider the possibility for importing electrolysis hydrogen from the Middle East or North Africa for use in hydrogen boilers in Germany. It is possible these locations could produce electrolysis hydrogen at a cost lower than even the lowest-cost hydrogen that is produced in the EU by 2050 because of the high solar capacity factors in this region. We retrieve the cost to produce electrolysis hydrogen in the Middle East from Perner, Unteutsch, and Lövenich (2018) (€1.73 per kg). We follow the same methodology as we do to calculate the shipping cost from Norway to Germany, using sea-distances.org to calculate the number of days it would take to ship the hydrogen via tanker from Egypt to Hamburg, Germany.

Residential heating technology and cost

We retrieve household space heating demand in 2015 from Fleiter et al. (2017). Fleiter et al. projects an overall 25% reduction in heating demand from 2015 to 2050 across the 14 EU member states it assesses, which we apply to 2015 residential space heating demand in our study. We assess four scenarios for heating single family houses in Germany: 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.

Two of our scenarios include an auxiliary hydrogen boiler for cold spells. Both heat pumps and fuel cell heaters may not provide sufficient heat during very cold temperatures. To determine the proportion of time that the auxiliary hydrogen boiler would be needed to supplement either a heat pump or fuel cell, we conduct an analysis of daily average temperatures in Germany from 1983- 1996 using typical meteorological year data (American Society of Heating, Refrigeration, and Air-Conditioning Engineers, 2001). We calculate that a heat pump or fuel cell could be used to meet 62% of the heating needs in a year, and the remainder of the time, an auxiliary boiler would be needed. We do not include heat storage in our assessment. Further detail on this calculation is available in Baldino et al. (2020).

Fuel cells generate primarily electricity but also heat and water as byproducts. We assume that the electricity generated would be used to supply the electricity needs of that residence and derive electricity demand for German residences in 2050 from Klaus, Vollmer, Werner, Lehmann, and Müschen (2010) and assume that excess electricity production would be sold to utility companies at the average wholesale price for renewable electricity in Germany in 2050, which is based on our projection of renewable electricity prices in Searle and Christensen (2018).

Results

Figure 1 compares the annual cost of the different heating options for single-family homes in Germany in 2050. We find that all air-source heat pump scenarios cost less than the hydrogen-only technologies. A German household using a stand-alone heat pump would spend 40%–60% less than a household using a hydrogen boiler, depending on the source of the hydrogen. Were a household in Germany need to use an auxiliary boiler for cold spells in addition to a heat pump, the total heating cost would still be 20%–50% less than it would using a hydrogen boiler alone, depending on the kind of hydrogen. Using a fuel cell heater would be the most expensive option for a household—around three times as expensive as using a hydrogen boiler with the same kind of hydrogen. The lowest-cost fuel cell scenario is still four times as expensive as the stand-alone heat pump scenario.

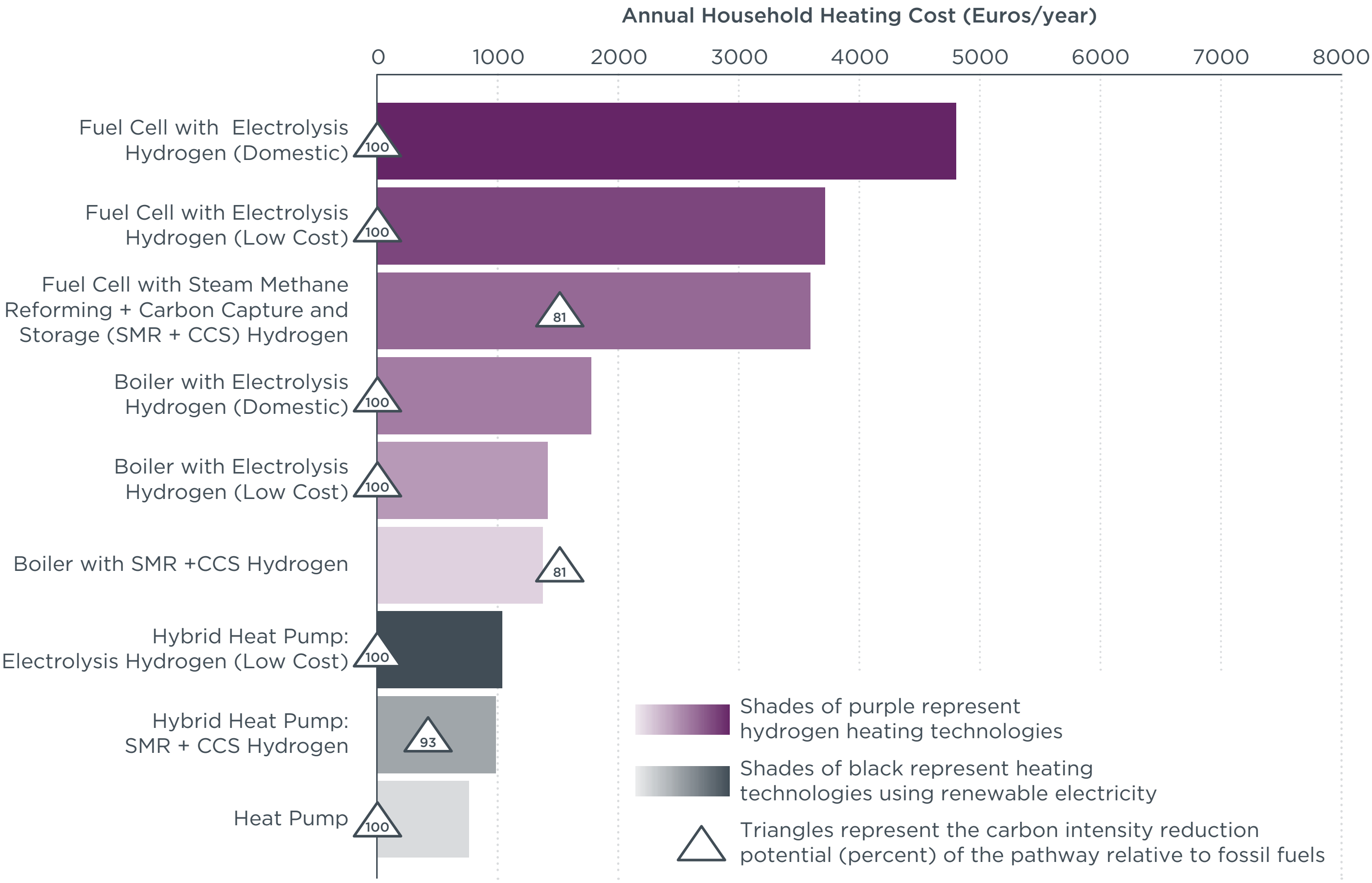

Figure 1. Cost comparison (in euros) and greenhouse gas intensity reduction potential of different technology options for heating a household for one year in Germany in 2050.

We find low-cost electrolysis hydrogen from Sweden to be slightly more expensive than SMR + CCS hydrogen and two-thirds the cost of electrolysis hydrogen produced domestically in Germany. The relative expense of each of the pathways using hydrogen are due to these differences in production costs. We also investigate how much it might cost to import electrolysis hydrogen from outside the EU, where it could be produced at a lower cost. The electrolysis hydrogen production cost in the Middle East estimated by Perner, Unteutsch, and Lövenich (2018) is half of our low-cost price estimate for Sweden. However, we find that the additional cost of shipping this hydrogen from the Middle East compared to Swedish electrolysis hydrogen would more than offset the production cost savings, resulting in the same cost for consumers to use in heating. This is because electrolysis hydrogen from the Middle East would need to be liquefied for shipping, while we assume that Swedish hydrogen could be supplied to Germany via existing or future pipelines. If it were not possible to use these pipelines in 2050, then it could cost less to import electrolysis hydrogen from the Middle East compared to Sweden.

Figure 1 also illustrates the GHG intensities of all heating pathways. It shows that all pathways based on renewable electricity from wind and solar are GHG neutral, providing a 100% reduction in greenhouse gases relative to natural gas. The pathways using SMR + CCS hydrogen have an average GHG intensity range of 5 gCO_2e/MJ to 22 gCO_2e/MJ, corresponding to a greenhouse gas reduction of 69%–93% for the SMR + CCS pathway compared to natural gas (represented as an average GHG reduction of 81% in Figure 1). Here, we assume that SMR + CCS processes improve their environmental performance compared to today and utilize some of the low-GHG hydrogen as a process fuel instead of natural gas. The SMR + CCS hydrogen would have a higher GHG intensity if natural gas were used as a process fuel. The range in greenhouse gas reduction potential for this pathway reflects a range of assumed upstream leakage rates during natural gas production and transport (0.5%–2%), as well as a range of carbon capture efficiencies (70%–90%) (Parkinson, 2019). The GHG intensity for the hybrid heat pump pathway is a weighted average of the renewable electricity needed for the heat pump and the SMR + CCS hydrogen needed for the auxiliary hydrogen boiler, based on the fact that the boiler would be used 38% of the year. Baldino et al. (2020) explains how we derive these GHG intensities in more detail.

Figure 2 illustrates the breakdown in total costs for each pathway between input energy (hydrogen or renewable electricity), capital expenses (CAPEX), and operating expenses (OPEX). It only illustrates pathways using SMR + CCS hydrogen, and the energy costs for the fuel cell scenario are net of the revenue from selling excess electricity to the grid. For each pathway, the input energy (hydrogen or renewable electricity) accounts for the majority of overall cost. For the 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. This figure shows that, while the CAPEX of a heat pump is greater than the CAPEX of a hydrogen boiler, the yearly expense for heat pumps is lower due to lower energy costs. 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. This is essentially because household-scale fuel cells are not a cost-effective electricity generation pathway.

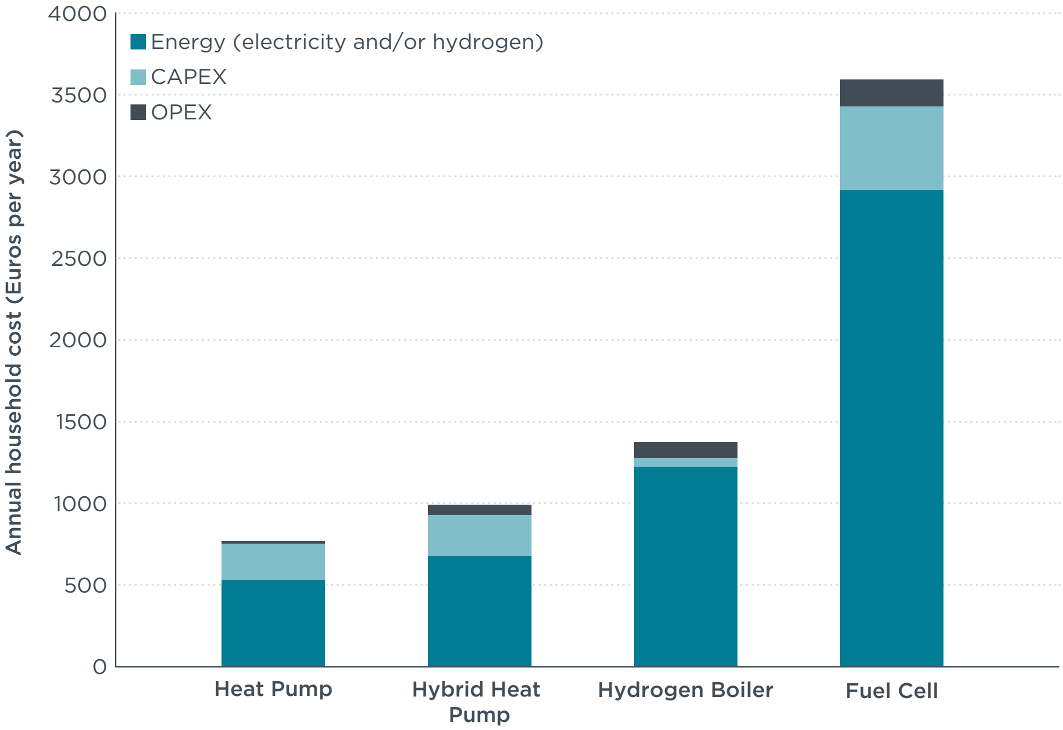

Figure 2. Cost components of heating pathways. The cost of energy for the fuel cell scenario is net of excess electricity generation that is sold to the grid. For the pathways using hydrogen, the hydrogen is from SMR + CCS.

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. Figure 3 illustrates a sensitivity analysis showing how changing energy prices would affect our findings. For all scenarios except fuel cells using SMR + CCS hydrogen, the lower and upper bounds of the error bars represent the full range of results we calculate when varying three parameters: natural gas prices, renewable electricity prices, and gas distribution fees and taxes. In this sensitivity analysis, we increase and decrease the costs for these three parameters by 50%. For the SMR + CCS hydrogen fuel cell scenario, a lower natural gas price leads to lower cost, while a high renewable electricity price increases the revenue from households selling excess electricity to grid operators and thus decreases the total cost of this pathway. The combination of these changes in the sensitivity analysis thus leads to a large reduction in costs for the fuel cell scenario using SMR + CCS hydrogen (the lower bound), while high natural gas prices and low renewable electricity prices would have the opposite effect (the higher bound). We find that the sensitivity analysis changes the cost of all heating scenarios by 20%–40%.

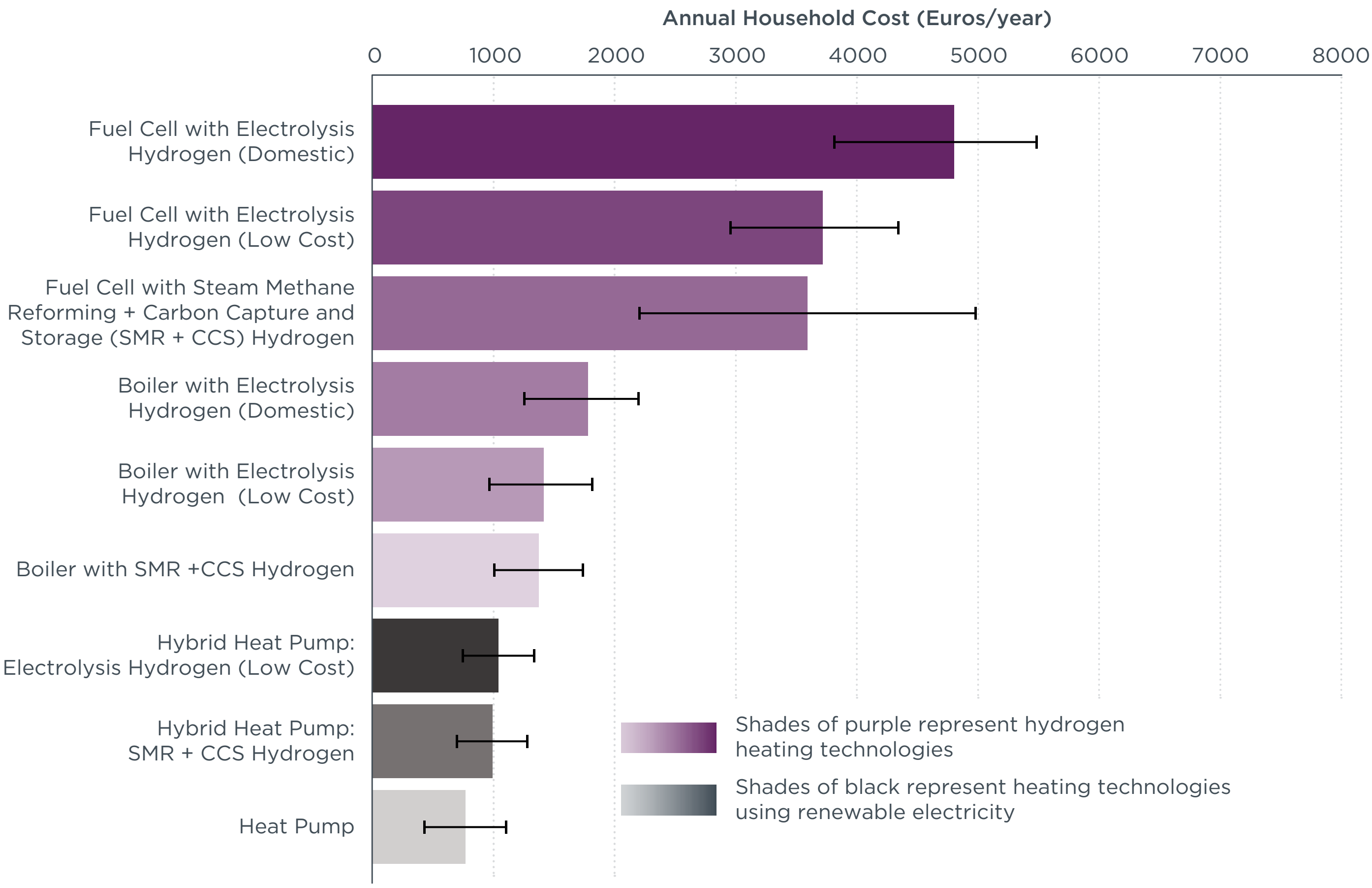

Figure 3. Sensitivity analysis (shown in error bars) on the cost of household heating.

All heat pump scenarios would remain the most cost-effective option even if renewable electricity prices were 50% higher or 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 assumptions. Even with a 50% change in energy prices, the fuel cell scenarios do not become cost competitive with the other pathways.

Discussion

Among the low-GHG or GHG-neutral residential heating pathways we assess, we find that using heat pumps with renewable electricity to heat a single-family home provides a cost advantage compared to using hydrogen in boilers or fuel cells in Germany. We also find that the heat pump scenarios offer strong GHG reductions compared to SMR + CCS hydrogen pathways, even when accounting for improvements in the environmental performance of this pathway. A stand-alone heat pump could possibly be sufficient to heat homes in Germany in 2050 due to expected climate warming and improved home insulation, but it is possible an auxiliary boiler would be needed. We find that any heat pump scenario, with or without an auxiliary boiler, provides the lowest-cost heating option for a single-family home in the Germany in 2050. A hybrid heat pump using SMR + CCS hydrogen results in less than 50% of the GHG emissions from pathways relying on SMR + CCS hydrogen only.

We find that electrolysis hydrogen offers the greatest GHG reductions of the hydrogen pathways in our analysis. Electrolysis hydrogen can be delivered at a similar cost to SMR + CCS hydrogen only if it is imported from countries that can produce it at a lower cost than Germany. Even if GHG emissions are greatly reduced for the SMR + CCS pathway compared to today, there are still significant GHG emissions from upstream natural gas leakage and incomplete CO_2 capture. We find that SMR + CCS hydrogen can provide only a 69%–93% reduction compared to fossil gas, while all pathways based on renewable electricity, including electrolysis hydrogen, are zero-carbon.

Compared to our other analyses of the UK and EU, and an upcoming study in the Netherlands, we find less of a cost advantage for heat pumps relative to the hydrogen heating scenarios. This is because we project the retail renewable electricity price in 2050 to be higher in Germany than the other regions due to lower wind and solar potential and high taxes and utility charges. In addition, in the hybrid heat pump scenarios, the auxiliary hydrogen boiler would need to be used a greater proportion of the year in Germany due to a greater number of cold spells compared to the other regions. However, despite these differences between our analysis in Germany and other regions, we still find the heat pump scenarios provide a cost advantage compared to all of the hydrogen heating scenarios. This finding holds even if renewable electricity prices are 50% more or natural gas prices are 50% less than we assume in our main scenarios.

Other studies exploring strategies to cost-effectively reduce the carbon impact of heating in Germany have arrived at similar conclusions as we do here. A Jülich Forschungzentrum study on Germany's energy transition found that the most cost-effective way for the country to achieve a 95% reduction in greenhouse gas emissions in 2050 relative to 1990 levels would be to deliver 83% of heat demand with renewable electricity, with heat pumps being the primary technology (Robinius, et al., 2019). Likewise, a Fraunhofer position paper on Germany's "hydrogen roadmap" states that buildings will not be a major source of hydrogen demand in the future, and most heat demand will be met with heat pumps using renewable electricity (Hebling et al., 2019). That paper states that only if there is limited renewable electricity available to Germany for use in heat pumps, either domestically or from imports, will there be a long-term potential for low-GHG hydrogen demand in buildings. They also write that hydrogen-powered fuel cell heating systems do not have market potential in the medium term. Another Fraunhofer study points to the lower efficiency of hydrogen heating pathways, as well as the reduced availability of electrolysis hydrogen in 2050 compared to expected heating demand, as the main reasons why heat pumps are the best options for the heating sector in Germany (Gerhardt et al., 2020).

Certainly, building efficiency measures will play an important role alongside any low-GHG heating pathway, and these measures will also increase the viability of using stand-alone heat pump in Germany. Some stakeholders, such as Agora Energiewende, posit that in the years leading up to 2030, efficiency measures will play the most important role in reducing the climate impact from heat (Buck, Graf, and Graichen, 2019). In our UK study, we find that the cost of reducing heat demand in a typical home in the UK by 15% through insulation and other efficiency measures is lower on a per-kWh basis than the cost of delivering heat through any of the heating pathways we include in our analyses (Baldino et al., 2020). This is an important consideration, given that a recent study found that reductions in heating demand in Germany over the past ten years have only been due to milder winters, not improvements in building efficiency. Additional incentives are necessary to improve energy efficiency in buildings (DIW Berlin, 2020). In the near term, COVID-19 stimulus packages in Germany could include grants to cover the cost of energy refurbishments (Quitzow & Letz, 2020).

A Deutsche Energie-Agentur report on the energy transition echoes the importance of building efficiency improvements as a necessity for achieving climate goals (Bründlinger et al., 2018). They argue, however, that their "technology mix" scenario, including a large portion of "power fuels" based on hydrogen, will help meet climate goals at lower cost than an electrification scenario relying heavily on heat pumps. For the heating sector, their "technology mix" scenario has more gas heating systems than heat pumps in buildings in Germany in 2050, which would require significant imports of hydrogen-based fuels. As our analysis of the cost to import electrolysis hydrogen from the Middle East illustrates, even if the Middle East can produce hydrogen at a lower cost than a European country, the cost to liquefy and ship this hydrogen negates the production cost benefits. We find that importing hydrogen from the Middle East for use in a boiler would be around the same cost as using low-cost European electrolysis hydrogen, and both of these pathways would still be 40% more expensive than our heat pump only scenario.

Similarly, the Hydrogen Council concludes that hydrogen solutions are some of the most cost-effective ways to support the heating sector's transition to low-GHG energy. That study estimates lower delivered electrolysis hydrogen costs for Germany than our analysis, and reports that the cost of renewable hydrogen production using offshore wind in Europe will drop to €2.05 (USD $2.50) per kg by 2030, based on economies of scale for electrolyzer manufacturing, "larger systems," and low-cost renewable electricity (Hydrogen Council, 2020). Based on Christensen (2020)'s methodology, however, we find that the lowest electrolysis hydrogen production costs in the EU in 2050 would be €3.50 per kg, 20 years later than the timeframe assessed in the Hydrogen Council study. The Hydrogen Council study also reports a cost of €2.70 per kg for shipping electrolysis hydrogen from Saudi Arabia to Germany in 2030. That study finds that more than half of the cost is due to production and the rest is due to distribution, e.g. shipping. This total price aligns with our finding for the cost of hydrogen delivered from the Middle East to Germany, based on Perner et al.'s projection of a hydrogen production cost, however we estimate this cost to become feasible in 2050, not 2030.

Further, Bloomberg New Energy Finance reports costs for electrolysis hydrogen that are much lower than what we find using Christensen (2020)'s assumptions, finding that Germany can achieve a cost of USD $4 per kg by 2050, which is around 40% lower than the cost we project based on Christensen (2020) ($6.41 per kg). In their *Hydrogen: The Economics of Space and Water Heating* report, BNEF estimates lifetime costs for the same heating pathways we include in our analysis (BNEF, 2019). Assuming "moderate heat demand," BNEF finds that, for a household in Germany, the lifetime cost of using an air-source heat pump for heating would be nearly at cost parity with a hydrogen boiler using electrolysis hydrogen, while using a fuel cell would be the lowest cost option of all the pathways. This is the opposite of our finding; we find that fuel cells using electrolysis hydrogen are the most expensive of the three options and that heat pumps provide a cost advantage of at least 40% compared to a hydrogen boiler, even if low-cost electrolysis hydrogen (from Sweden) were used in the boiler.

Conclusions

This study assesses the cost and GHG performance of low-GHG heating options for Germany in 2050. We find that fossil-based hydrogen cannot completely decarbonize heating because of upstream natural gas leakage and incomplete carbon capture. Even in a scenario where 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. In contrast, the use of wind and solar power for heat pumps and electrolysis hydrogen would be fully zero-carbon.

We find that using zero-carbon electricity in heat pumps will provide the greatest cost advantage for single-family households in Germany in 2050 out of the low-GHG heating options we consider, while fuel cells using electrolysis hydrogen from zero-carbon electricity are the most costly. Using a heat pump to heat a home is at least 40% lower cost than all hydrogen heating scenarios in our analysis. Hybrid heat pumps using hydrogen in an auxiliary boiler are the second most cost-effective heating pathway in our analysis, 20%–50% less expensive than using a standalone hydrogen boiler. Importing electrolysis hydrogen from countries within and outside the EU that can produce it inexpensively would provide a cost advantage to the hydrogen-based heating pathways compared to using electrolysis hydrogen produced domestically in Germany.

We recognize that there is considerable uncertainty in 2050 heating costs in our analysis and identify that much of this uncertainty stems from future natural gas and renewable electricity prices. In a sensitivity analysis, we find that even if renewable electricity prices were 50% higher or natural gas prices 50% lower than our central assumptions, heat pumps are still the most cost-effective heating option in 2050. At the same time, 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, remain. These factors will impact the costs of heating in 2050 in a way that is difficult to predict today.

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