The role of hydrogen in German residential buildings

Kevin Knosala,[a, 1] Lukas Langenberg,[a] Noah Pflugradt,[a] Peter Stenzel,[b] Leander Kotzur,[a] and Detlef Stolten[a,c]

[a] Forschungszentrum Jülich GmbH, Institute of Techno-economic Systems Analysis (IEK-3), Wilhelm-Johnen-Str., 52428 Jülich, Germany

[b] TH Köln, Cologne Institute for Renewable Energy (CIRE), Betzdorfer Straße 2, 50679 Köln, Germany

[c] Chair for Fuel Cells, RWTH Aachen University, c/o Institute of Techno-economic Systems Analysis (IEK-3), Forschungszentrum Jülich GmbH, Wilhelm-Johnen-Str., 52428 Jülich, Germany

Abstract

Fossil-fueled heating in the building sector is responsible for 16% of Germany's total CO_2 emissions. Options for the climate-neutral heating of buildings include renewable electricity or renewable hydrogen. In this paper, we conduct a bottom-up study to investigate the role of hydrogen in the climate-neutral energy supply of ten selected residential buildings in comparison to electricity-based systems. Based on a demand simulation and linear optimization of the supply system, sensitivity analyses identify the threshold values of the hydrogen price for the use of hydrogen technologies (hydrogen boilers or fuel cells) in building energy systems and make the quantities of hydrogen consumed visible.

The results specify the first installations of hydrogen-operated fuel cells in multi-family houses if the hydrogen price reaches 0.17 €/kWh_{H2} in 2050 at an electricity price of 0.31 €/kWh_{el}. Generally, for different building types and electricity supply prices, it indicates that the use of hydrogen becomes economically-viable if the price of hydrogen supply is in the range of 34–61% of the price of the electricity supply per kWh and below.

For the case of green hydrogen obtained using renewable electricity, it is highly questionable whether hydrogen supply will be that much cheaper than direct electricity supply, making its economical use in buildings uncertain.

Keywords

Hydrogen, residential buildings, heat supply, renovation, price sensitivity, bottom-up modeling, linear optimization, fuel cell, hydrogen boiler, heat pump, microeconomic, projection

---

[1] *Corresponding author. E-mail address: k.knosala@fz-juelich.de (K. Knosala)*.

Abbreviations: GHG – greenhouse gas, SFH – single-family house, TH – Terraced House, MFH – multi-family house, AP – apartment building, CHP – combined heat and power, COP – coefficient of performance, CAPEX – capital expenditures, OPEX – operational expenditures, TAC – total annualized cost, PEM – proton exchange membrane, SOFC – solid oxide fuel cell, PV – photovoltaic, LOHC – liquid organic hydrogen carriers, MILP – mixed-integer linear program, T^{sup} – Supply temperature

1 Introduction

With the Climate Protection Act of 2021, the German government set the goal of reaching climate-neutrality in all sectors by 2045 [1]. As of 2020, the building sector accounts for 16% of Germany's total CO_2 emissions due to the use of fuels for heating and hot water generation [2]. To achieve a greenhouse gas (GHG) neutral building sector, the National Hydrogen Strategy explicitly specifies the use of hydrogen in the heating market as one of its integral components, in addition to the electrification processes already taking place [3]. One way to use hydrogen in the building sector is by repurposing existing infrastructure, such as the conversion of the natural gas grid and building energy system devices to use hydrogen. Figure 1 displays the transformation from left to right. The first phase comprises the transition from the state-of-the-art natural gas grid to a demonstration grid operating with a blend of hydrogen. This is currently being carried out by the Cadent and Northern Gas Networks in the UK. The HyDeploy project aims to demonstrate technical feasibility by blending 20% hydrogen into a distribution grid by 2023 [4]. A similar project is being implemented by Netze BW in Germany, who plan to demonstrate a blend of up to 30% hydrogen in the gas grid by 2023 [5]. Blending hydrogen into the gas grid is theoretically possible and is already being tested as stated before, but it should be mentioned also that due to the lower volumetric energy density of hydrogen compared to natural gas, only 6.6% of CO2 emissions can be saved with 20% blending of hydrogen [6]. The final transitional step is a gas infrastructure that runs exclusively on hydrogen which, e.g., is the goal of the H21 project currently being implemented by Northern Gas Networks in the UK [7]. This new hydrogen infrastructure could consist of actual new construction or the repurposing of the existing natural gas infrastructure. The decentralized generation, storage, and utilization of hydrogen would further enable hydrogen supply for buildings for which there was no existing gas grid, or for which new construction would be too expensive.

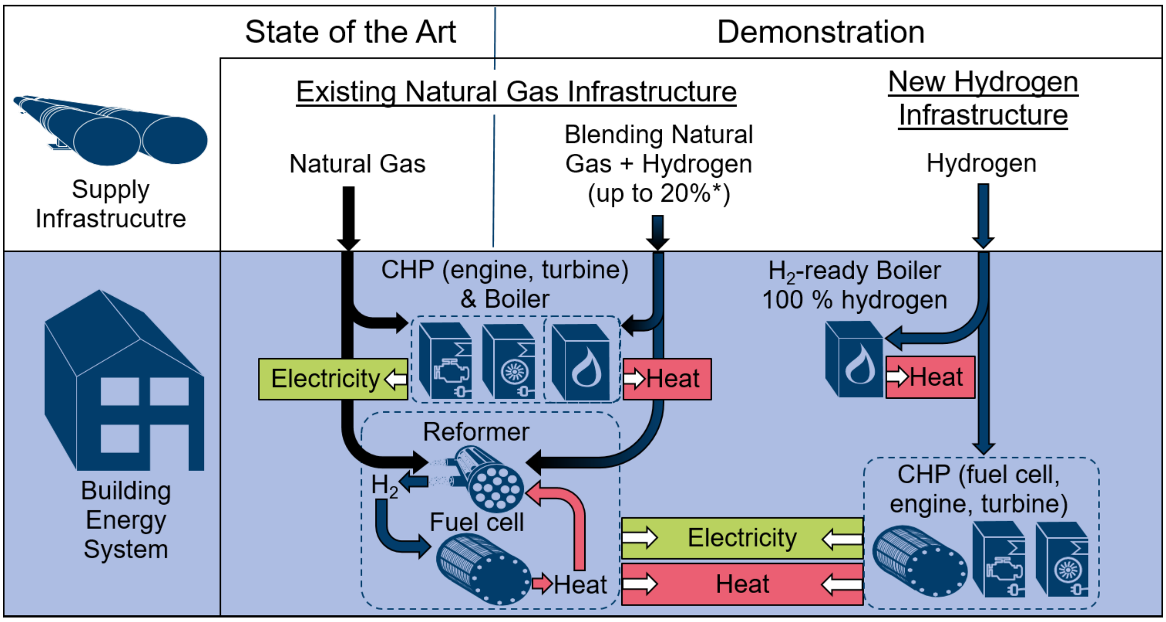

Figure 1. Transition of the supply infrastructure and building energy systems from natural gas to hydrogen operation.

The role that hydrogen will play in building energy systems will depend heavily on its price and the heat production costs of hydrogen technologies compared to alternatives, especially heat pumps. Regarding this topic, the Hydrogen Council presented a study in which the competitiveness of hydrogen in various sectors was examined. It revealed that falling costs for hydrogen will be a primary driver of its competitiveness. For the building sector, a comparison with heat pumps reveals a threshold price by which the use of hydrogen becomes the more economical alternative, at 4.54 €/kg_{H2} (0.14 €/kWh_{H2}, or 49% of the current German electricity price and 64% of the average European electricity price)[2] for renovated buildings and 2.52 €/kg_{H2} (0.08 €/ kWh_{H2}, 28% of the current German electricity price and 36% of the average European electricity price) for new ones [8], excluding the required transmission and distribution infrastructure.
The production cost of climate-neutral hydrogen differs largely on the basis of the production technology, but is already reaching the stated threshold. According to a report by the International Renewable Energy Agency, green hydrogen produced by electrolysis powered by renewable electricity cost more than 5 €/kg_{H2} (0.15 €/kWh_{H2}) in 2020. However, that is two to three times as high as the price for blue hydrogen, which is produced from fossil natural gas, including storage of the resulting CO_2 [9].

1.1 Literature review

In 2010, the European Parliament issued a directive specifying that all new buildings must be nearly energy-neutral by 2021. This new standard prescribes low-energy demand among buildings, which is to be met to a substantial extent using renewable sources [10]. As a flexible clean energy carrier, hydrogen is increasingly seen as an important element in the decarbonization of the building sector [11]. In 2020, the European Commission published a strategy paper that outlined the European hydrogen roadmap. This strategy, in the long term, aims for widespread green hydrogen production from wind and solar power sources to supply all sectors, with net-zero emissions to be reached by the year 2050 [12]. In the most ambitious scenario for 2050, the European hydrogen roadmap sees hydrogen as a decisive factor in heat supply for the building sector. The sector is projected to account for 26% of hydrogen demand, which corresponds to 579 TWh_{H2} [13]. In Germany, the National Hydrogen Strategy also includes infrastructure for hydrogen generation, transport, storage, and usage that is interconnected both nationally and at the European level. It is primarily based on existing natural gas grids that must be adapted to the particular physical and chemical properties of hydrogen to enable its use in the heating of residential buildings [3], [14].
Despite the importance of hydrogen being increasingly recognized by researchers and policymakers alike, energy scenarios are pessimistic regarding its role in the building sector. Gerhardt et al. published a study on the use of hydrogen in the future energy system, with a focus on heating in buildings [15]. In addition to the low energy efficiency of heating using hydrogen, they cite the high hydrogen demand of the building sector and high conversion costs for hydrogen boilers as militating against its use and advocate the extensive use of heat pumps, even without any renovation of existing buildings. Other studies focusing on building energy supply do not consider hydrogen a relevant technology. They consider only heat pumps and district heating for heat supply [16]–[19]. Hanley et al. reviewed the role of hydrogen across different energy scenarios with different areas of focus [20], concluding that there is a correlation between hydrogen's penetration of energy systems and policy ambitions such as the integration of renewable sources or decarbonization targets. In a review paper, Quarton et

---

[2] For the conversion between gravimetric and energetic values the lower heating value of hydrogen (33.33 kWh/kg) is considered.

al. investigate the inconsistent role that hydrogen currently plays in global energy scenarios [21]. For this, they considered the model approaches behind the scenarios, as well as the assumptions underlying the data. Based on the studies surveyed, they assume a minor role for hydrogen in the heating of buildings and a great opportunity in the industrial and transportation sectors. With respect to energy system modeling approaches, Quarton et al. are also pessimistic about hydrogen. The reasons for this include the low level of detail of the modeling, as well as temporal variability. Brandon and Kurban see a vital opportunity in hydrogen for the decarbonization of heat but also a major challenge in the transformation of the energy system. They identify a need for government targets and policy measures to develop hydrogen infrastructure and production at scale [11]. In turn, Bothe and Janssen conducted a study to investigate the role of hydrogen in the German heating market, with a focus on hydrogen boilers and heat pumps [22]. They conclude that hydrogen in the heating market can reduce system costs and the cost burden for low-income households. In addition, importing hydrogen could help meet the challenge of limited domestic renewable energy potential. In their policy brief on an adaptive hydrogen strategy, Ueckerdt et al. see uncertainties regarding the decarbonization of the entire building sector [23].In this sector, hydrogen for heat supply competes with alternatives, above all heat pumps, whose evaluation will often depend on the boundary conditions on site. For example, the efficiency-related cost advantages of heat pumps in some existing buildings are diminished by energy refurbishment measures. In densely populated areas where heat grids are available, the use of hydrogen in fuel cells or other CHP systems could also play a role, but here too it competes with more efficient large-scale heat pumps. In summary, for the current study situation it can be said that heat pumps are certainly used for a large part of the heat supply in the building sector, but there are uncertainties for a part of the building stock, where the benefits of heat pumps and hydrogen technology are close to each other. The exciting question is how large this part is.

Schiro et al. investigated the hydrogen compatibility of domestic gas boilers and found that admixtures of up to 20% hydrogen with natural gas are possible. Mixtures with a higher hydrogen content require a higher fuel flow to achieve the same thermal load due to the lower heating value of hydrogen. Furthermore, if the hydrogen content exceeds 20%, burners must be redesigned to prevent the risk of unintended ignition and flashbacks [24]. Worcester-Bosch, a leading manufacturer of gas boilers, expects that hydrogen-ready boilers will have the same costs as current natural gas ones [25]. Furthermore, the retrofit of existing natural gas units with new burner tips and controls requires little effort. Nationwide conversion measures have already been implemented in the conversion from town to natural gas, which can serve as an example [26]. As a field test for hydrogen heating, an apartment complex in the Netherlands was heated using 100% hydrogen by means of hydrogen-ready boilers. The project aims to demonstrate heating using pure hydrogen and its distribution over an existing natural gas pipeline [27]. Staffell et al. discuss systems that consume hydrogen and provide combined heat and power (CHP) as an alternative to hydrogen-ready boilers [26]. Of these CHP systems, they identify fuel cells as being the most efficient and having the lowest emissions. For residential applications, proton exchange membrane (PEM) and solid oxide fuel cells (SOFCs) are typically chosen, featuring micro-CHP components due to their comparatively low capacities. At present, fuel cells are still expensive, but their prices are rapidly decreasing. Between 2012 and 2018, the price halved to about 8400 €/kW_{el}, and their service lifetimes increased, due to their diffusion, especially in Japan and Europe [26]. At present, fuel cell systems are operated using natural gas but can also be converted into hydrogen with minor modifications. Nastasi evaluated the environmental advantages of micro-CHP systems in buildings that operate with blends of close to 20%-vol hydrogen in natural gas [28], which results in direct emission reductions of only 7%.

A big disadvantage of heating with hydrogen, compared to the use of heat pumps, is low efficiency. The London Energy Transformation Initiative presented an independent report in

February 2021 in which two routes for heating buildings were compared: Using green hydrogen for boilers and electricity with heat pumps [29]. They state that using green hydrogen would be approximately six times less energy-efficient compared to the use of heat pumps. In addition, the use of green hydrogen would require a 150% increase in primary energy generation [29].

1.2 Research objectives

The literature review highlights that in many scenario studies, hydrogen is considered to play little or no role in the building sector. Quarton et al. trace the pessimistic results regarding hydrogen in this sector to a low level of detail in the models and low temporal variability [21]. Thus, the aim of this paper is to provide a detailed techno-economic analysis of ten selected buildings that are typical of the German building stock. This analysis compares hydrogen-based building energy systems with those based on renewable electricity for the target years 2020 and 2050 with consideration to the building standard. It does not consider the national energy system as a whole, but looks at individual buildings. In contrast to the studies cited, we develop an individual microeconomic optimization (building owner perspective), rather than a macroeconomic one. For this purpose, the analysis is carried out in two steps. First, cost-optimal supply systems are determined for each building at fixed costs for hydrogen and electricity to make the preference of the energy carrier choice and its technological use visible. In the second step, sensitivity analyses are conducted to highlight the threshold values of hydrogen use and corresponding technologies. We utilize typical building types to derive initial and basic statements regarding the question of how the role of hydrogen in German buildings should be evaluated for the years 2020 and 2050 from a technical and microeconomic perspective.

2 Methodology and basis data

In this study, an optimization of climate-neutral building energy systems is carried out with the aim of minimizing investment and operating costs using a mixed-integer linear program (MILP) optimization model. For this goal, we proceeded as shown in Figure 2. We selected ten buildings built between 1919 and 2016 from an existing archetypal building catalog to serve as examples, with the aim of covering as wide a range of building types as possible. For these buildings, demand profiles and renewable generation profiles for heat pumps and photovoltaic (PV) systems were created. These profiles served as inputs for building energy system models containing the technical and economic parameters of various supply systems powered by renewable electricity or green hydrogen. During the optimization process, the dimensions and operation of a cost-optimal energy system for each building was determined for the offered supply technologies.

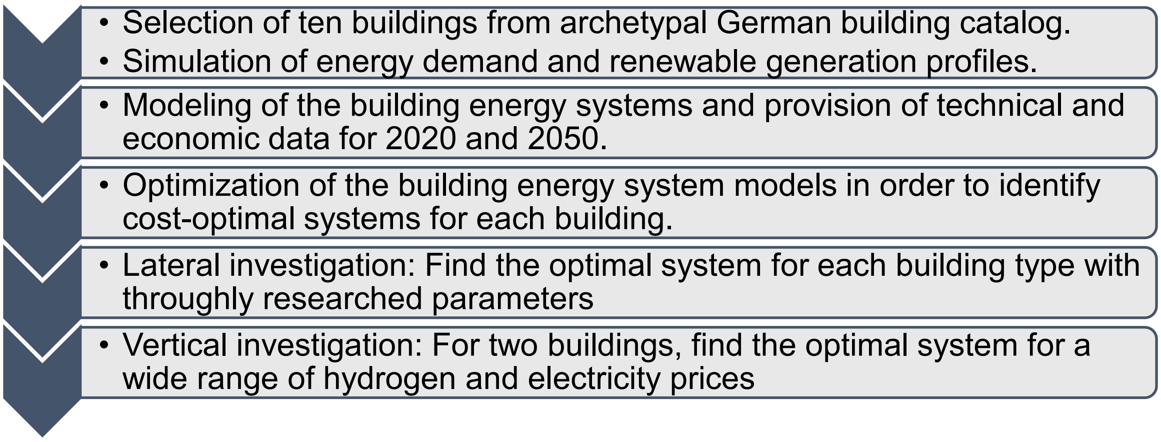

Figure 2. Flowchart depicting the methodological procedures followed in this study.

2.1 Basis building data and simulation of demand and renewable generation profiles

The parameters of the thermal conductivity of the building hull for typical buildings in Germany from the TABULA database served as input parameters for the heat demand simulation. The TABULA database contains the physical building characteristics of archetype buildings from different construction years that are representative of the entire German building stock [30]. There are 40 generic buildings in total, divided into four types, namely single-family houses (SFHs), terraced houses (THs), multi-family houses (MFHs), and apartment buildings (ABs) with building years ranging from 1859 to 2016. In this study, we limit our selection to ten of these archetypal buildings with construction years between 1919 and 2016. These buildings were selected to be as different, and to cover as wide a range of building archetypes, as possible. The buildings considered were seven SFHs with terraced and detached construction styles, as well as three MFHs consisting of 6, 12, and 20 households; ABs were not considered. The basic building parameters for each selected building are presented in Table 5.

The optimization of building energy systems has the goal of determining the energy requirements of the systems in a cost-optimal manner. These energy requirements are represented by electricity and heat load profiles, which are simulated with an hourly resolution using the Python packages Load Profile Generator (LPG)[3] and Time Series Initialization for Buildings (TSIB),[4] which have been developed at our institute and are freely available online.

LPG simulates the behavior of every single resident (or agent) of a household based on a personal preferences model and generates corresponding activity profiles. Based on these, individual demand for hot water and electricity is determined. The activity profiles and hot water demand are then passed on to the TSIB to calculate the total heat demand. Here, the heat output of single residents is calculated based on their activity profiles. Furthermore, the heating load is determined using a simplified 5R1C thermal building model [31], which combines the heat transfer coefficients of the selected buildings from the TABULA database and the heat output of the individual residents. Together with the weather data on outside irradiance and air

---

[3] Load Profile Generator (LPG), available at: https://github.com/FZJ-IEK3-VSA/LoadProfileGenerator

[4] Time Series Initialization for Buildings (TSIB), available at: https://github.com/FZJ-IEK3-VSA/tsib

temperature, the load profiles for heating are simulated [32]. For each of the ten buildings, the building envelopes are considered without renovation, and with two different renovation levels, with each of the three having different heat supply temperatures. If no renovation is considered, the original building envelope from the TABULA database is used. Regarding the renovation levels, level one reduces specific heating demand by 74% and level two by 78% compared to an unrenovated building for the oldest SFH selected. The renovation costs, specific heat demand levels, and the heat supply temperature for each building and all three renovation levels, are shown in Table 6 of the Appendix.
As these levels of renovation were each considered for the ten selected buildings, 30 heating profiles were generated. Figure 3 lists the selected buildings by building year, house type, and number of inhabitants per household. The diagram also displays the living space per household, as well as its specific heat demand and level of renovation.

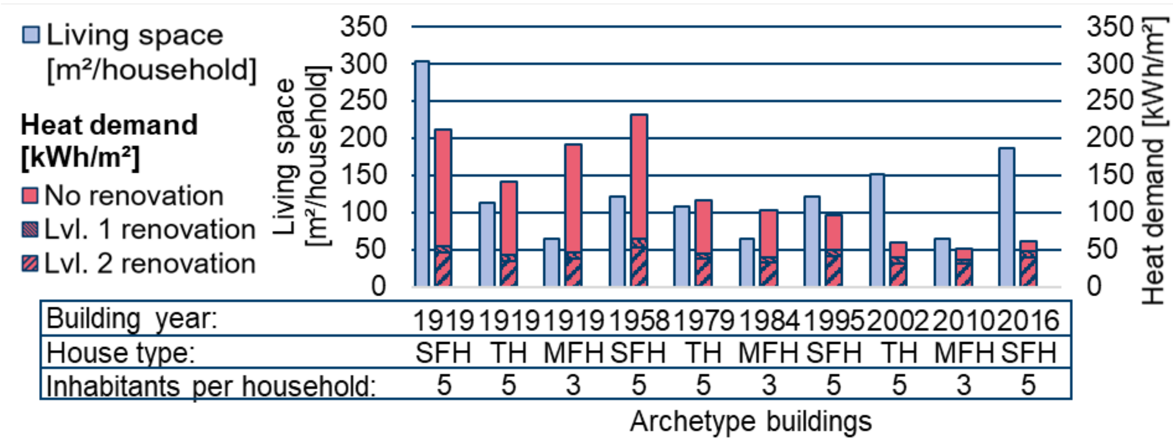

Figure 3. Building selection from the German building stock with living space and heat demand for three different levels of renovation.

In addition to the demand profiles, there is also a need for the time series of the possible generation power of heat pumps and PV systems as inputs for the energy system optimization. These renewable generation profiles are calculated using the already-mentioned Python package TSIB, in accordance with Knosala et al. [33].

2.2 Assumptions regarding the hydrogen supply price

As hydrogen cannot yet be obtained for use in residential buildings, a theoretical price is derived from literature values for the years 2020 and 2050.[5] Regionally-produced hydrogen is assumed for 2020 and imported hydrogen for 2050. The production costs of green hydrogen for the year 2019 range from 0.08 to 0.19 €/kWh_{H2}, according to a report by the International Renewable Energy Agency (IRENA) [34]. This range is due to various influencing factors, such as fluctuations in the price of electricity or the number of operating hours. In addition to production costs, there are costs for transportation. For regional production, the U.S. Department of Energy assumes a transport price of around 0.045 €/kWh_{H2} [35]. As a result, the production of green hydrogen and its regional transport result in 0.13–0.23 €/kWh_{H2}, regarding the lower heating value of hydrogen. For distribution to residential buildings in

[5] All price assumptions are in $€_{2020}$.

Germany, an average network fee of 0.0156 €/kWh$_{H2}$ was charged by network operators in the year 2020 [36]. The gas supplier also charges costs for distribution and its margin in the amount of approximately 0.02 €/kWh$_{H2}$ [37]. In addition, a sales tax of 19% applies, whereas a gas tax, which is primarily intended to serve climate policy goals, is not considered for green hydrogen due to its climate-neutrality [38]. Thus, the theoretical costs for regionally-produced green hydrogen for use in German residential buildings in the year 2020 are between 0.2 and 0.31 €/kWh$_{H2}$. In this paper, the import of globally-produced hydrogen is assumed for the year 2050. According to Heuser, the global costs for green hydrogen at the export harbor will range from 0.09 to 0.15 €/kWh$_{H2}$ [39]. In addition, Heuser expects transport via ship and liquid organic hydrogen carriers (LOHCs) to cost 0.01 €/kWh$_{H2}$. For transport within Germany, we assume current distribution costs. This is an optimistic estimate, because the expected decrease in the transported quantity of gas will likely lead to increased specific distribution costs. Including the same net fee for distribution, charges of the gas supplier and sales tax as 2020, in 2050 imported hydrogen is expected to cost between 0.17 and 0.24 €/kWh$_{H2}$ for use in German residential buildings, as per published data. According to the aforementioned report from IRENA, hydrogen production costs could reach 0.026 €/kWh$_{H2}$ in 2050 [34]. Together with the pure transmission costs in the exporting country, which according to Heuser amount to about 0.03 €/kWh$_{H2}$, as well as the above-mentioned costs for taxes, distribution and charges incurred in Germany, a hydrogen price of up to 0.12 €/kWh$_{H2}$ can be expected [39]. In this paper, we assume a price of hydrogen for end users of 0.25 €/kWh$_{H2}$ for 2020 and 0.2 €/kWh$_{H2}$ for 2050, as listed in Table 4.

An indicator to show the difference between gas and electricity prices is described by their percentage ratio, calculated as the quotient of gas and electricity prices, as they can be determined at the respective times based on market prices for both energy carriers. The lower this gas-to-electricity price percentage ratio, the more the electricity price is above the gas price per kWh. For natural gas in Europe in 2020, this percentage ratio ranges from 46% in the Netherlands to 20% in Belgium [40], [41]. Germany has the second-lowest percentage ratio with 21%, whereas the European average was around 30% in 2020. For locally-produced green hydrogen, the price ratio depends on the local price of electricity. As a result, the average price ratio for hydrogen can only drop below one if it functions as a seasonal storage for renewable electricity or if hydrogen is imported from sun-rich countries at lower prices than locally-produced hydrogen.

2.3 The modeling of building energy systems

The cost-optimal energy system design and operation for each building is determined during the optimization process. For this purpose, a pool of components is parameterized, from which the energy systems can then be assembled. The building energy system model investigated in this study is based on renewable electricity and green hydrogen as energy carriers, as well as the energy conversion and storage components displayed in Figure 4.

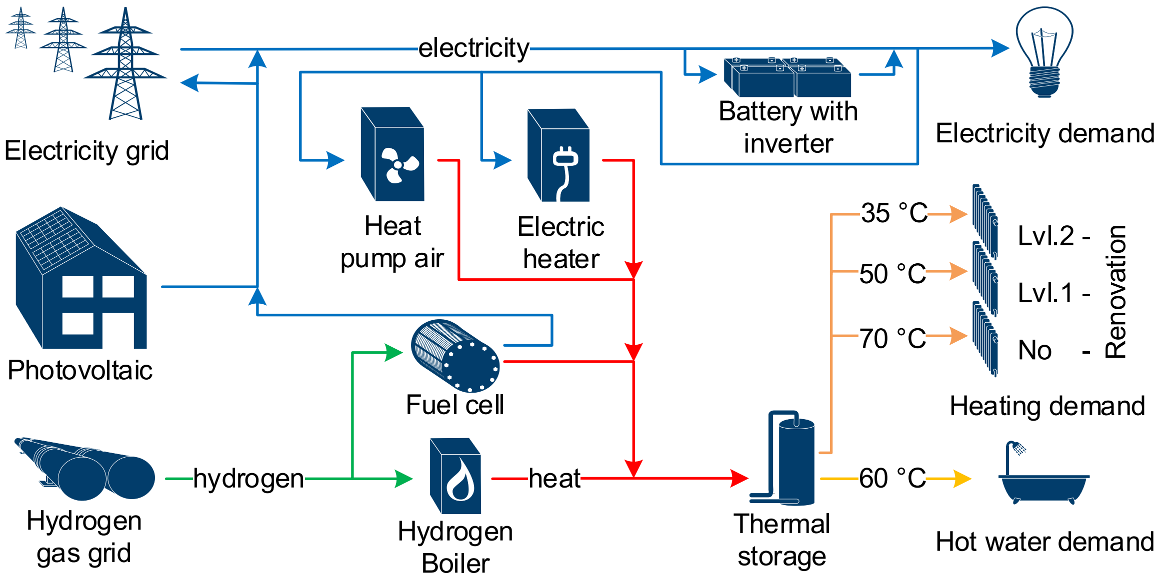

Figure 4. Technology pool and interconnection of possible building energy systems.

The energy system model can draw hydrogen from the hydrogen gas grid and electricity from the public power grid, as well as generate its own electricity with a photovoltaic system. If hydrogen is purchased from the public grid, we assume that this grid, including connection of the end consumer, is available and all corresponding costs are included in the assumed hydrogen price. Electricity can be converted into heat with an electric heater, as well as with a heat pump. The heat pump is an air source type that is modeled as three different sub-components, each with a different heat supply temperature, T^{Sup} (35, 50, and 70 °C), depending on the level of renovation and a fourth for the supply of hot water at 60 °C. For each sub-component, the hourly coefficient of performance (COP) is calculated according to its T^{Sup}. The calculated COP time series for the three sub-components are shown in Figure 17 in the Appendix. A discounted tariff for the operation of the heat pump and the income from the feed-in of surplus electricity are defined here as shares of the electricity price. The more favorable heat pump tariff is offered to electricity customers in Germany by the power grid provider and municipalities. It is based on the fact that lower network charges and concession fees have to be paid and in return, the grid provider has access to the heat pump and can shut it down if demand on the grid is too high. [42]. It is assumed to be 70% of the normal price for electricity. Income from feeding surplus electricity into the grid results in a revenue of 16% of the present electricity price. This corresponds to a heat pump tariff of 0.22 €/kWh$_{el}$ at an electricity price of 0.31 €/kWh$_{el}$ and revenues for feeding electricity into the grid of 0.05 €/kWh$_{el}$ in both 2020 and 2050. We assume a constant electricity tariffs for end users as it is currently the case for most households in Germany. With the introduction of smart metering systems, it is likely that more flexible rates will be available in the future. Thus, it is not clear how the price volatility on the energy market will be passed to the end user.
Hydrogen from the public gas grid can be converted into heat by means of hydrogen boilers, or into heat and electricity in fuel cells. The fuel cell is modeled as two different sub-components, depending on the respective technology. The SOFC generates 600 °C of heat [43], which is then reduced to 90 °C to be used in the system and that can operate in a modulating fashion between 33 and 100% of its capacity. The PEM-FC has a heat output of

60 °C and modulates freely between 0 and 100% of its capacity. For CHP systems, a CHP-Index of 0.05 €/kWh$_{el}$ is assumed for electricity feed-in into the grid [44]. Regarding storage components, the technology pool contains a lithium–ion battery and a thermal storage system that is set to a capacity of 300 liters. To represent a single thermal storage unit with multiple levels of temperature, the system is modeled as five sub-components sharing the storage volume with temperatures of 35, 50, 60, 70, and 90 °C each. With these sub-components, the heat demands are met. As previously noted, the temperature level of the heat demand depends on the level of renovation. Figure 4 illustrates the levels, which are supplemented by hot water demand. A sink that can be used to remove excess heat from the system was also modeled.

The model contains two sets of parameters, each of which is for the years 2020 and 2050. Economic parameters, as shown in Table 1 for 2020 and Table 2 for 2050, were defined for the system components, both for purchasable energy carriers, salable electricity, and the subsidy for fuel cells. For heat pumps, we can expect equipment costs to fall while installation and material costs will likely rise. Because of the high shares of labor and supplementary costs from the total costs for the installation of heat pump systems, we assume the same system costs for both target years (on a 2020 basis). Based on the assumption in the previous section, the price for hydrogen for the year 2020 is assumed, relatively conservatively, to be in the upper third of the price range of green hydrogen stated by Powell of 0.25 €/kWh$_{H2}$ [45]. For the year 2050, we assume that the price of green hydrogen is reduced to 0.2 €/kWh$_{H2}$. The technical parameters are presented in Table 3, both for 2020 and 2050.

Component	**Capex**				**Opex**				**Lifetime**		**Source**
	Fix		Variable		Fix		Variable				
Photovoltaic system	1000	€	1300	€/kW$_{el}$	10	€	13	€/kW$_{el}$	20	years	Own as.
PEM fuel cell	7000	€	10000	€/kW$_{el}$	300	€	20	€/kW$_{el}$	10	years	Own as.
SO fuel cell	7000	€	10000	€/kW$_{el}$	600	€	0	€/kW$_{el}$	10	years	Own as.
Heat pump	5000	€	600	€/kW$_{th}$	50	€	6	€/kW$_{th}$	20	years	Own as.
Electric heater	100	€	60	€/kW$_{th}$	0		1.2	% Inv./a	20	years	Own as.
Hydrogen boiler	2800	€	100	€/kW$_{th}$	42	€	1.5	% Inv./a	20	years	Own as.
Thermal storage	23	€	34	€/kWh$_{th}$	0		0		25	years	Own as.
Lithium-ion battery	2000	€	700	€/kWh$_{el}$	0		0		15	years	[46]

Table 1. Economic parameters for 2020. Parameters from internal sources at the IEK-3 are marked as own assumptions (own as.). The costs for the balance of plant, energy management, and safety controlling systems are included in the component costs. We assume an annual economic interest rate for building owners of 3%. CAPEX: capital expenditures, OPEX: operational expenditures; PEM: proton–exchange membrane; SO: solid oxide.

Component	**Capex**				**Opex**				**Lifetime**		**Source**
	Fix		Variable		Fix		Variable				
Photovoltaic system	1000	€	650	€/kW_{el}	10	€	6.5	€/kW_{el}	20	years	[47, p.]
PEM fuel cell	4000	€	1500	€/kW_{el}	120	€	45	€/kW_{el}	15	years	[48]
SO fuel cell	4000	€	1500	€/kW_{el}	120	€	45	€/kW_{el}	15	years	[48]
Heat pump	5000	€	600	€/kW_{th}	50	€	6	€/kW_{th}	20	years	Own as.
Electric heater	100	€	60	€/kW_{th}	0		1.2	% Inv./a	20	years	Own as.
Hydrogen boiler	2800	€	100	€/kW_{th}	42	€	1.5	% Inv./a	20	years	Own as.
Thermal storage	23	€	34	€/kWh_{th}	0		0		25	years	Own as.
Lithium–ion battery	1000	€	200	€/kWh_{el}	0		0		15	years	[46]

Table 2. Economic parameters for 2050. Parameters from internal sources at the IEK-3 are marked as own assumptions (own as.). Costs for the balance of plant, energy management, and safety controlling systems are included in the component costs. We assume an annual economic interest rate for building owners of 3%. CAPEX: capital expenditures, OPEX: operational expenditures; PEM: proton–exchange membrane; SO: solid oxide.

Component	**Efficiency**			**Source**	
		2020	2050	2020	2050
Inverter	η_{el}	97 %	97 %	Own assumptions	
PEM fuel cell	η_{el}	55 %	55 %	Own assumptions	
	η_{th}	30 %	30 %	Own assumptions	
SO fuel cell	η_{el}	55 %	55 %	Own assumptions	
	η_{th}	30 %	30 %	Own assumptions	
Heat pump at 35 °C	COP_{min}	3.3		Own calculations according to [50]	
	COP_{max}	5.0			
Heat pump at 50 °C	COP_{min}	2.7		Own calculations according to [50]	
	COP_{max}	4.6			
Heat pump at 70 °C	COP_{min}	2.2		Own calculations according to [50]	
	COP_{max}	3.5			
Electric heater	η_{th}	95 %	100 %	Own assumptions	

Hydrogen boiler	η_{th}	100 %	100 %	Own assumptions	
Lithium–ion battery	η_{charge}	95 %	95 %	[46]	[51]
	$\eta_{discharge}$	95 %	95 %	[46]	[51]
	Self-discharge	0.01 %/h	0.01 %/h	Own assumptions	[51]
Thermal storage	η_{charge}	99 %	99 %	[50]	
	$\eta_{discharge}$	99 %	99 %	[50]	
	Self-discharge	0.1 %/h	0.1 %/h	Own assumptions	

Table 3. Technical parameters for 2020 and 2050.

2.4 Cost-minimal design and operation

During the optimization process, the cost-minimal energy system for each building is determined, together with its operational profile. For this, the energy systems, as described in chapter 2.2, were modeled as a MILP within the Framework for Integrated Energy System Assessment (FINE)[6] [52]. The optimization goal is to minimize the total annualized cost of each building's energy system for the target years of 2020 and 2050.

For this purpose, this paper presents two investigations. First, the optimal total annual costs are determined for each building with a fixed electricity and hydrogen price for each target year. The electricity price for Germany is assumed to be 0.308 €/kWh$_{el}$ for both target years, and 0.218€/kWh$_{el}$ for use in heat pumps. Regarding hydrogen, a price of 0.25 €/kWh$_{H2}$, referring to the lower heating value, is assumed for 2020, and 0.2 €/kWh$_{H2}$ for 2050.

For the second study, we performed a sensitivity analysis of hydrogen and electricity prices in the ranges presented in Table 4. This study was intended to identify the thresholds of the hydrogen price at which it would become economically-viable to switch to a hydrogen-based system. In addition, this approach can be used to identify how the amount of hydrogen used, as well as the exact choice of technologies, depends on the ratio of the price of electricity and hydrogen.

In both studies, the renovation costs and reduced heating demand due to improved insulation, as listed in Table 6 in the Appendix, are considered.

	Commodity	Price		Source
Subsidy-, purchasing and sales prices for both approaches	Photovoltaic subsidy for electricity sold into the grid (only for 2020)[7]	0.0316	€/kWh$_{el}$	Own assumptions
	Electricity purchasing for heat pumps (2020 & 2050)	0.218	€/kWh$_{el}$	Own assumptions
	Electricity sales (2020 & 2050)	0.05	€/kWh$_{el}$	Own assumptions

[6] Framework for Integrated Energy System Assessment (FINE), available at: https://github.com/FZJ-IEK3-VSA/FINE

[7] The subsidy is paid in addition to the price for electricity sales.

Approach	Commodity	Price		Source
Approach 1: Fix commodity prices	Electricity purchasing (2020 & 2050)	0.308	€/kWh$_{el}$	Own assumptions
	Hydrogen purchasing (2020)	0.25	€/kWh$_{th}$	Own assumptions
	Hydrogen purchasing (2050)	0.2	€/kWh$_{th}$	Own assumptions
Approach 2: Sensitivity analysis	Commodity	Price range		Source
	Electricity purchasing (2020 & 2050)	0.15, 0.18, …, 0.62	€/kWh$_{el}$	Own assumptions
	Hydrogen purchasing (2020 & 2050)	0.05, 0.06, …, 0.4	€/kWh$_{th}$	Own assumptions

Table 4. Prices for the subsidy, purchasing, and sale of commodities for both analytical approaches.

3 Results

This chapter presents the results on the role of hydrogen in German buildings. This is split into two sections: In a lateral investigation, we examined the selected buildings and their cost-optimal energy systems for fixed prices for the purchasing of electricity and hydrogen. For choosing the prices, we used the literature assumptions detailed above. In a vertical investigation, we show the sensitivity of the electricity and hydrogen prices with the aim of identifying the quantitative use of energy sources and the technology selection made. Finally, in order to gain more profound insight into the impact of a declining hydrogen price on technology selection and renovation efforts, the development of energy systems is also viewed at a more detailed building level for two selected buildings.

3.1 Lateral investigation: Optimal total annual cost with fixed electricity and hydrogen prices

The first analysis presented in this study examined the selected buildings and their cost-optimal energy systems for fixed prices for the purchasing of electricity and hydrogen. Figure 5 illustrates the total annual cost structure of cost-optimal energy systems regarding the examined SFHs and THs for both target years, considering the renovation levels. Figure 6 illustrates the same for MFHs. For the target year 2020, building energy systems use heat pump systems with a high share of electricity drawn from the grid for all three building types. These results are consistent with those of Gerhardt et al., who argued for the widespread use of heat pumps [15]. The results for the target year of 2020 also indicate that the renovation of buildings that were originally built before 1990 is part of the optimal total annual cost structure for lowering heating demand. That the cost-optimal renovation of buildings is performed after 30 years is in accordance with the recommendations of the European Commission, which notes an equally long period in its delegated regulation from 2012 [53].

The results for the target year of 2050 are similar to those for 2020. Heat pumps are used for heating in all of the buildings studied and hydrogen plays no role with the assumed costs of 0.25 €/kWh$_{H2}$ for 2020 and 0.2 €/kWh$_{H2}$ for 2050. Due to the same energy system structure in 2020 and 2050, renovation also makes economic sense in this target year for buildings built before 1990. Figure 5 and Figure 6 also show the annual COP of the heat pumps that were chosen in the cost-optimal energy systems, as well as the heating temperatures. As can be expected, the annual COP depends significantly on the heating temperature. Detailed heat pump data for the optimized buildings and their renovation levels regarding heating temperature, as well as the annual COP, power and heat generation of the heat pumps, is shown in Table 7 in the Appendix.

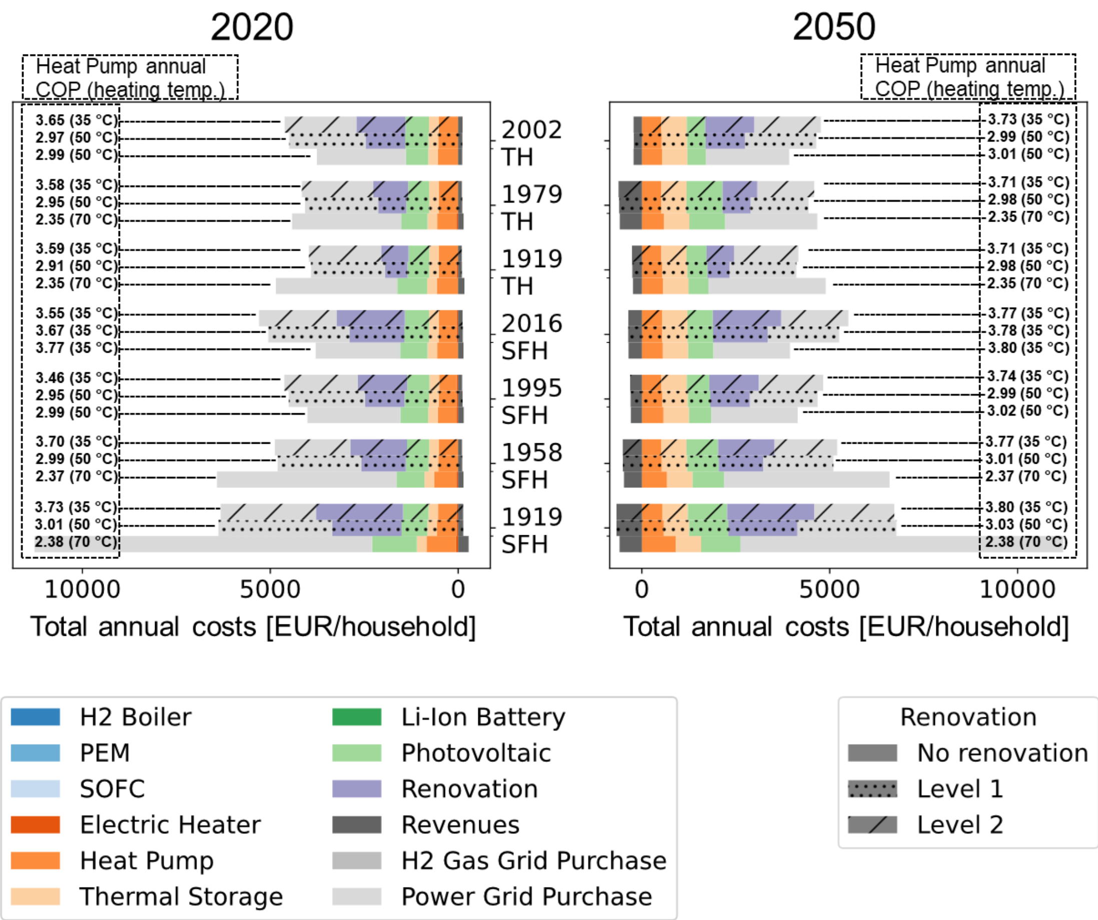

Figure 5. Optimal total annual cost structure for the examined SFHs and THs sorted by building year and renovation level, including the annual COP of heat pumps and the heating temperature per building and renovation level.

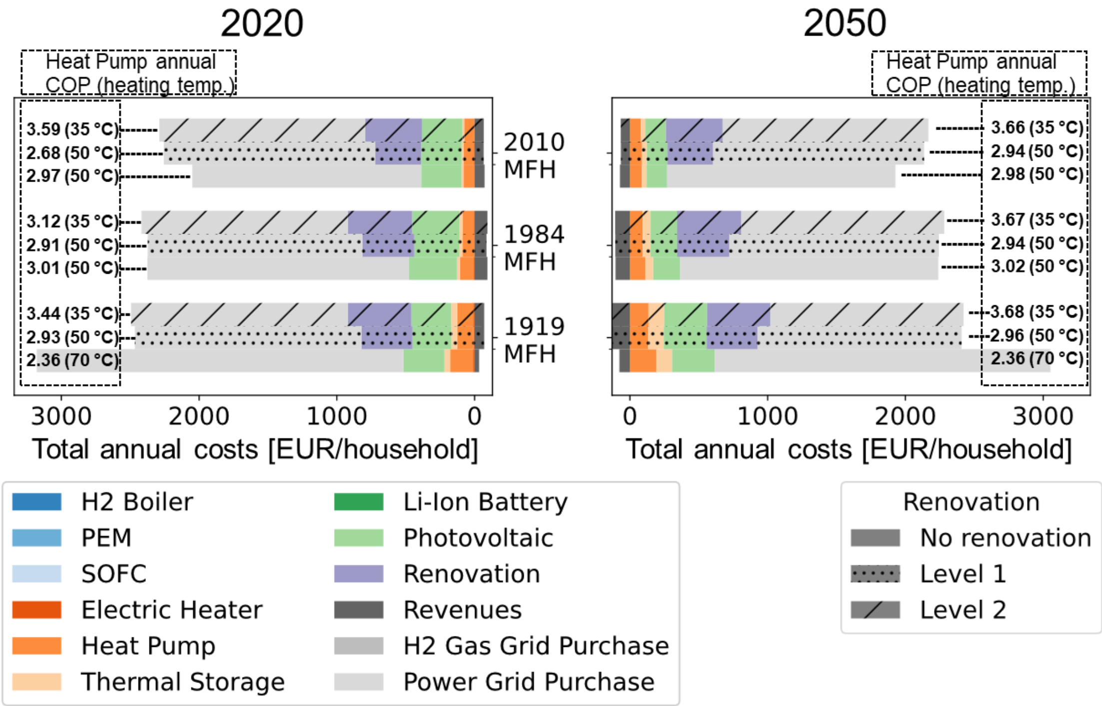

Figure 6. Optimal total annual cost structure for the examined MFH sorted by building year and level of renovation, including the annual COP of heat pumps and the heating temperature per building and renovation level.

3.2 Vertical investigation: Sensitivity analysis of the hydrogen and electricity price

In the second analysis, the sensitivity of the electricity and hydrogen price is analyzed with the aim of identifying the quantitative use of energy sources and the technology selection made to determine a general threshold price for hydrogen use in all of the buildings analyzed. In order to gain more profound insight into the impact of a declining hydrogen price on technology selection and renovation efforts, the development of individual energy systems is also viewed from this perspective. In this second step, we identify threshold prices for the degree of hydrogen utilization in individual buildings.

3.2.1 Hydrogen usage by building type

The results shown in Figure 7 indicate the threshold values for the economically viable use of hydrogen in the selected SFHs and THs with building years of 1995 and 2002. The colors indicate how strong the share of hydrogen in the heat supply of the considered buildings is. For values above one, where more hydrogen is consumed than is needed for heating, hydrogen is also used for electricity generation using CHP. From 2020 to 2050, the price thresholds for hydrogen supply technology for the assumed electricity price of 0.31 €/kWh$_{el}$ are 0.11 €/kWh$_{H2}$ for 2020 and 0.13 €/kWh$_{H2}$ for 2050. The assumed hydrogen prices for 2020 (0.25 €/kWh$_{H2}$) and 2050 (0.2 €kWh$_{H2}$) can also be seen in Figure 7. There was virtually no use of hydrogen in 2020 and 2050 due to the economic advantage of electricity in its assumed price range. From these results, a percentage ratio of the hydrogen price in relation to the price of electricity can be derived, below which the use of hydrogen is economically-viable. These percentage ratios range between 34 and 45% for 2020 and 41 and 46% for 2050 for the examined SFHs. The SFHs built in 2016 exhibit significantly lower threshold values of 0.09 €/kWh$_{H2}$ (percentage ratio H_2/elec. of 29%) for 2020 and 0.11 €/kWh$_{H2}$ (percentage ratio H_2/elec. of 35%) for 2050. The lower benefit of hydrogen indicated by this is due to the efficient building standard and the low required heat supply temperatures of 35 °C, which makes heat pumps more reasonable than the use of hydrogen with high heating temperatures.

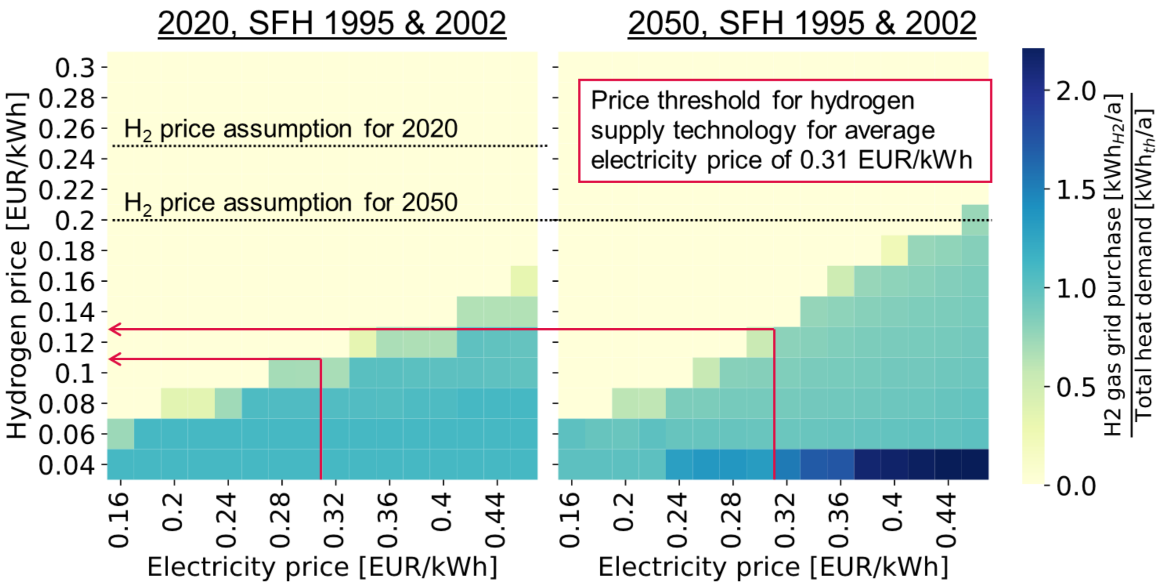

Figure 7. Price sensitivity for SFHs and THs with the building years 1995 and 2002 using cost-optimal technology configurations and renovation choices. The colors indicate the factor of hydrogen purchasing to total heat demand (space heating and hot water) in kWh per year.

Figure 8 shows the results for SFHs with building years from 1919 to 1979. Here, the price thresholds for hydrogen supply technology for the assumed electricity price of 0.31 €/kWh$_{el}$ are at 0.13 €/kWh$_{H2}$ for 2020 and 2050. As the only deviation, the 2020 value for the SFH built in 1958 is 0.11 €/kWh$_{H2}$. The derived percentage ratio of the hydrogen price in relation to the price of electricity ranges between 36 and 46% in 2020 and between 42 and 45% in 2050.

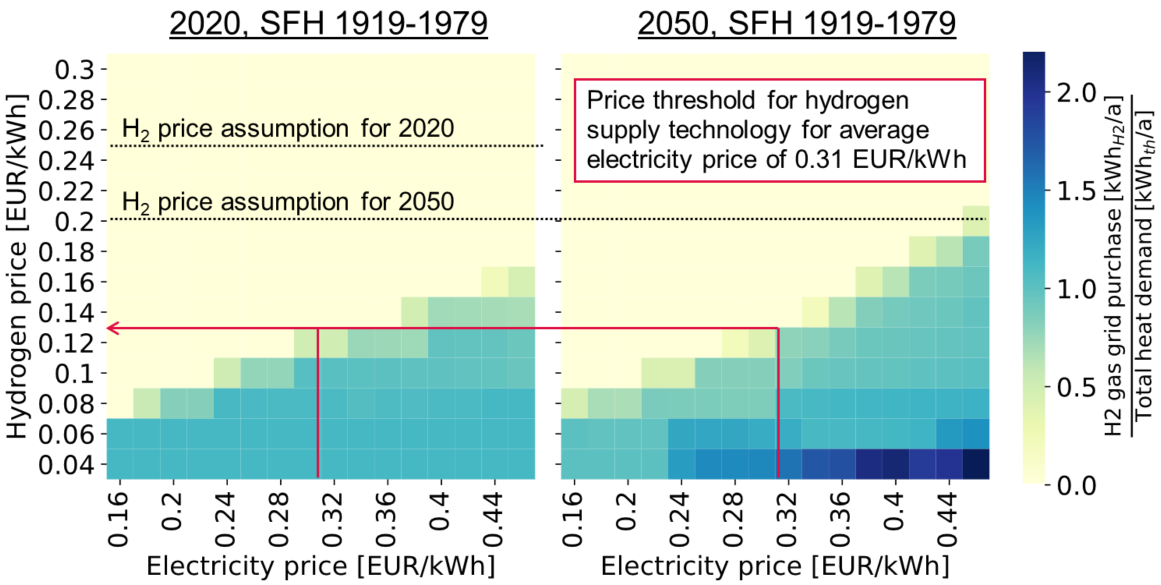

Figure 8. Price sensitivity for SFHs and THs with building years between 1919 and 1979 with cost-optimal technology configurations and renovation choices. The colors indicate the factor of hydrogen purchasing to total heat demand (space heating and warm water) in kWh per year.

A slightly different picture can be drawn for MFHs. For these buildings, the price threshold for hydrogen supply technology for the assumed electricity price of 0.31 €/kWh$_{el}$ increases significantly between 2020 and 2050, from 0.11 €/kWh$_{H2}$ to 0.15 €/kWh$_{H2}$ for the MFH built in 1919 and from 0.13 €/kWh$_{H2}$ to 0.19 €/kWh$_{H2}$ for MFHs built in 1984 and 2010. The two MFHs from 1984 and 2010 are shown in Figure 9. These results indicate that hydrogen is more economically-viable in MFHs than SFHs and THs, and becomes even more viable in the year 2050 for MFHs. The reason that hydrogen is used more in 2050 than in 2020 in MFHs is that fuel cell CHP systems are used for the cogeneration of heat and power. These fuel cell CHP systems are assumed to be less expensive in 2050 than 2020, and so, in contrast to SFHs, where hydrogen boilers are used, the use of hydrogen becomes more economically viable in 2050 than in 2020. The percentage ratio of the hydrogen price in relation to the price of electricity derived for 2020 ranges from 39 to 44% and between 54 and 61% for 2050.

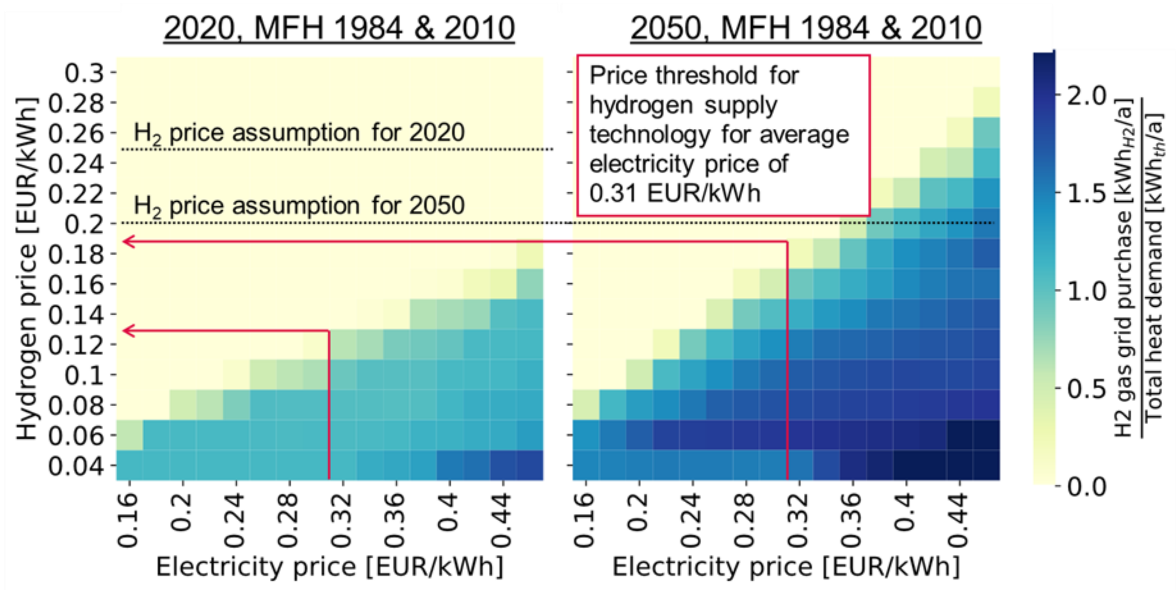

Figure 9. Price sensitivity for MFHs built in 1984 and 2010 with cost-optimal technology configurations and renovation choices. The colors indicate the factor of hydrogen purchasing to total heat demand (space heating and warm water) in kWh per year.

3.2.2 Technology selection by building type

The cost-optimal technology selection for SFHs and THs built in 1995 and 2002 depending on the price of hydrogen and electricity can be seen in Figure 10. These results support the analysis in chapter 3.1, and illustrate the minor role of hydrogen in 2020. For the target year of 2050, the technology selection features a combination of different technologies. For a hydrogen price below 0.08 €/kWh$_{H2}$ and a low electricity price, hydrogen boilers are favored. With an increasing hydrogen price, fuel cells are combined with heat pumps. Fuel cells alone are only used when a high electricity price meets a low hydrogen price of less than 0.05 €/kWh$_{H2}$ and the price of hydrogen is at a maximum of 16% of the electricity price. For both target years, heat pumps alone, and in combination with electric heaters, are preferred.

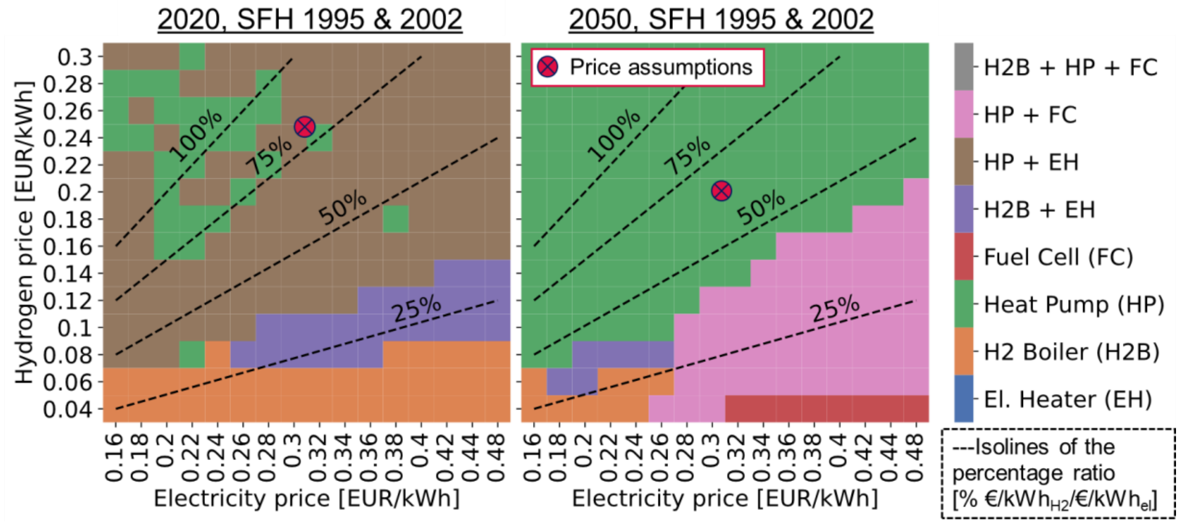

Figure 10. Price sensitivity for SFHs and THs built 1995 and 2002 with cost-optimal technology configurations and renovation choices. The colors indicate the predominant supply technology for heating over the building type group.

For SFHs and THs with building years between 1919 and 1979, the cost-optimal energy system structure is shown in Figure 11. The use of hydrogen is similar to that of the previously considered buildings, with the combination of hydrogen boiler and electric heater being used more frequently in 2050.

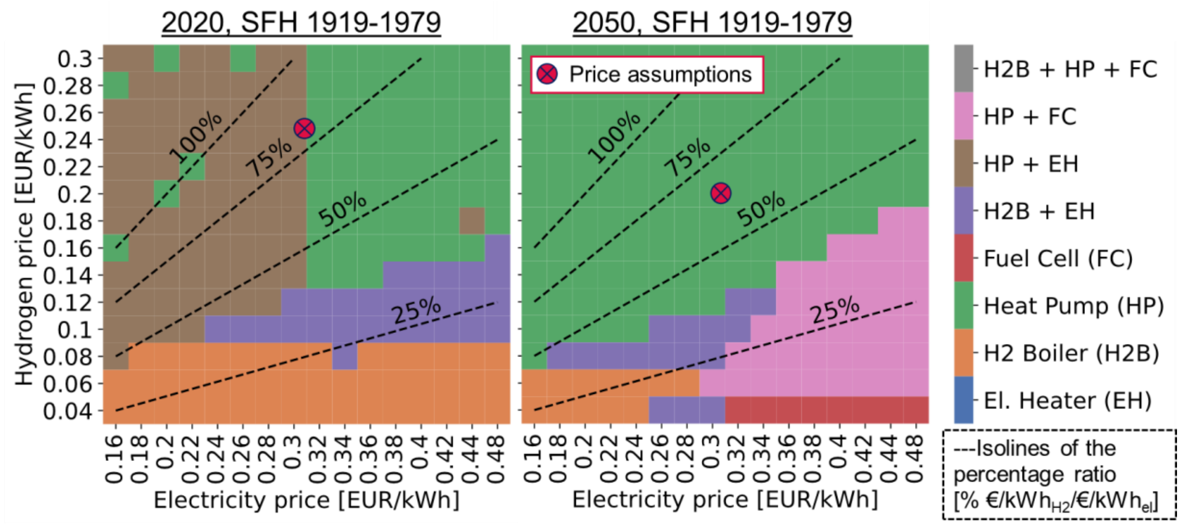

Figure 11. Price sensitivity for SFHs and THs built between 1919 and 1979 with cost-optimal technology configurations and renovation choices. The colors indicate the predominant supply technology for heating over the building type group.

The technology selections for MFHs, depending on hydrogen and electricity prices, are displayed in Figure 12. For the target year of 2020, the use of heat pumps already in the previous chapter identified can be observed, in combination with electric heaters. If the ratio of hydrogen and electricity prices decreases in favor of hydrogen, the combination of hydrogen boilers and electric heaters can be used in cost-optimal systems. In the case of an extreme high electricity price and a low price for hydrogen, fuel cells become part of cost-optimal energy systems. For 2050, fuel cell systems are used in combination with heat pumps. If the hydrogen price is lower, the aforementioned combination is extended by means of hydrogen boilers. Fuel cell systems are economically-reasonable, as they provide both heat and electricity. For this reason, fuel cell systems are used on their own if the percentage ratio of the hydrogen price in relation to the price of electricity is below 14%. This is the case if the electricity price is in the extreme high end of the assumed range above 0.35 €/kWh$_{el}$ and the hydrogen price is extremely low, below 0.05 €/kWh$_{H2}$, which is an unrealistic constellation.

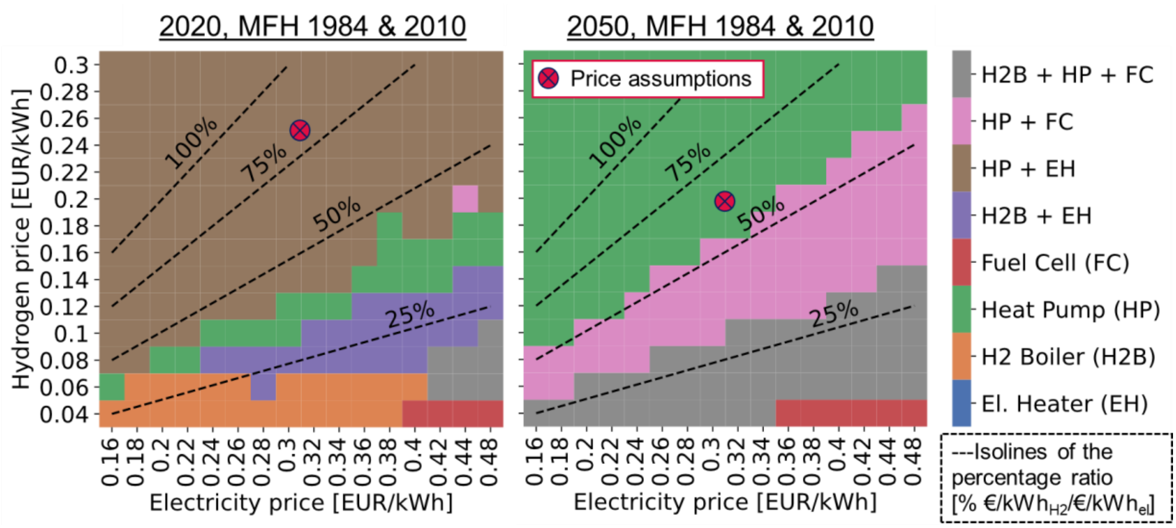

Figure 12. Price sensitivity for MFHs with cost-optimal technology configurations and renovation choices. The colors indicate the predominant supply technology for heating over the building type group.

3.2.3 Hydrogen-sensitive system structure for two selected buildings

A more profound insight into the structure and operation of building energy systems, dependent on the price of hydrogen, is provided by the results presented in this section. Individual buildings are investigated and include the technology selection and use of hydrogen, as well as the electricity drawn from the grid and own PV production. Furthermore, the renovation choice and resulting heat generation, including hot water, is presented, all of which depend on the price of hydrogen. The price of electricity is assumed to be 0.308 €/kWh$_{el}$ for the selected target year of 2050. The results are presented for two of the ten selected buildings from this study. The total annualized cost of energy supply for all combinations of supply prices for electricity and hydrogen for the two typical buildings can be found in Tables Table 8 and Table 9 in the Appendix.

First, a single-family TH in 2050 is considered, which was built in 1979 and features 108 m² of living area. The optimization results for this building can be seen in Figure 13. Without renovation, its annual heat generation, including warm water, is nearly 15,000 kWh$_{th}$. For the lowest assumed hydrogen price of 0.04 €/kWh$_{H2}$ (percentage ratio H_2/elec. of 13%), an SOFC is used with a hydrogen boiler and an electric heater. The SOFC is used instead of a PV system to generate electricity in addition to heat. For all hydrogen prices above, a PV system is built to generate electricity. Up to a hydrogen price of 0.10 €/kWh$_{H2}$ (percentage ratio H_2/elec. of

32%), a hydrogen boiler with an electric heater is used for heat generation purposes. For a hydrogen price of 0.12 €/kWh$_{H2}$ (percentage ratio H_2/elec. of 39%), the operation of the hydrogen boiler is significantly reduced by half, and a renovation choice is made to reduce the heat demand. Above 0.13 €/kWh$_{H2}$ (percentage ratio H_2/elec. of 42%), hydrogen is no longer used in the building's energy system, and heat pumps are used instead.
Based on this development, two threshold prices of the degree of hydrogen utilization for the year 2050 can be identified for the considered TH that was built in 1979. With a hydrogen price of up to 0.13 €/kWh$_{H2}$ (percentage ratio H_2/elec. of 42%), heating is primarily performed with hydrogen, in part with minor support from an electric heater. At this threshold, the building is renovated for a lower heating demand. Beyond this threshold price, hydrogen is no longer utilized, and a heat pump is used instead. For renovation measures, the observed building indicates that a low hydrogen price of up to 0.10 €/kWh$_{H2}$ (percentage ratio H_2/elec. of 32%) leads to the fact that no renovation must be carried out for a cost-optimal building heat supply.

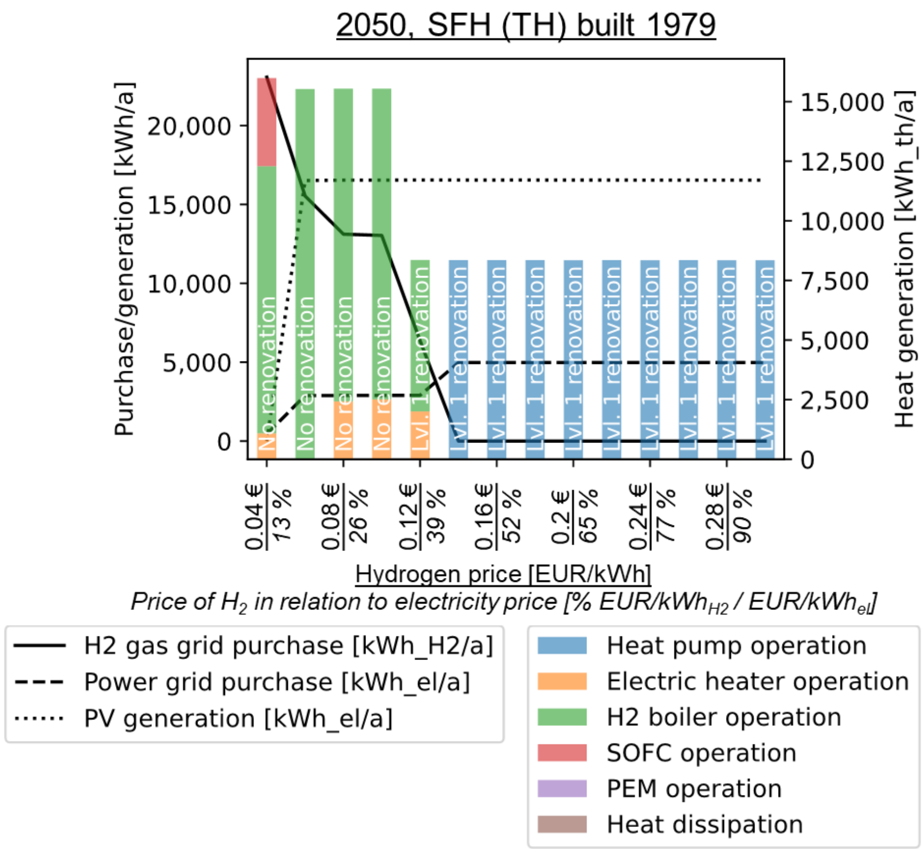

Figure 13. Price sensitivity for a TH (built in 1979, 108 m² living area) with its cost-optimal technology configuration and renovation choices for 2050.

For the second building, an MFH optimized for 2050 was chosen, which was built in 1984 with a total living area of 778 m² for 12 households. This corresponds to a living area per household of close to 65 m². Figure 14 presents the optimization results for this building. It shows that the lowest assumed hydrogen price results in limited PV production and heat generation through a combination of heat pumps, hydrogen boilers, and SOFCs. With an increasing hydrogen price, PV production is maximized and increasingly more heat is generated by the heat pump and less by the hydrogen boiler and SOFC. At a price of 0.17 €/kWh$_{H2}$ (percentage ratio H_2/elec. of 55%), a significant change in the system structure can

be observed. At this price, no more hydrogen is purchased, and the heat demand is then covered exclusively by the heat pump.
Based on this development of hydrogen utilization as a function of an increasing hydrogen price for the year 2050, a threshold value of 0.17 €/kWh$_{H2}$ (percentage ratio H_2/elec. of 55%) for the hydrogen price can be derived for the analyzed MFH built in 1984.

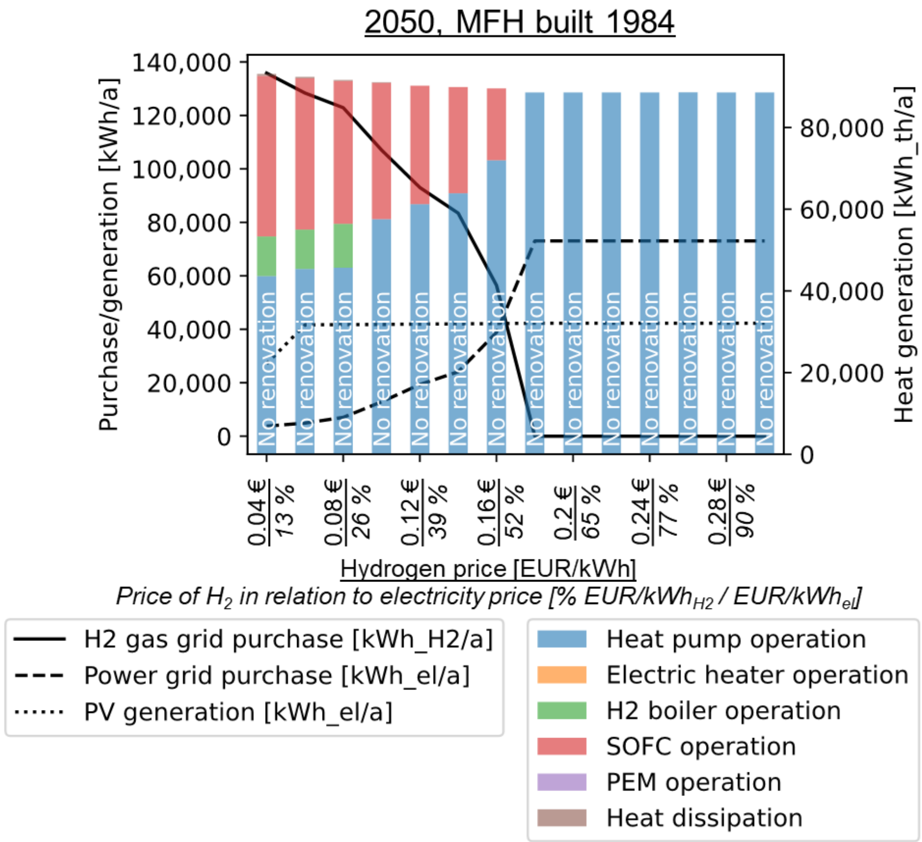

Figure 14. Price sensitivity for an MFH (built in 1984, with 778 m² total living area for 12 households) with the cost-optimal technology configuration for 2050. Renovation measures were not part of the optimal system here.

4 Discussion

In this study, we have identified threshold prices for the use of hydrogen in ten cost-optimized buildings, as is illustrated in Figure 15. With these results, we aim to derive initial basic statements regarding the role of hydrogen for typical buildings from the German building stock. It is important to note, that the assumption of constant electricity tariffs is a simplification that allows the calculation of a direct ratio between the electricity and hydrogen supply price. Tariffs for electricity might become more flexible in the future and change the incentives structure for residential buildings. However, it is not clear how the price volatility on the energy market will be passed to the end user.
For the examined SFHs, including terraced houses, a hydrogen price of up to 0.11 €/kWh$_{H2}$ (percentage ratio H_2/elec.-price of 35%) for 2020 and 0.13 €/kWh$_{H2}$ (percentage ratio H_2/elec.-

price of 42%) for 2050 leads to the use of hydrogen in building energy systems. Due to its efficient building structure and low required supply temperatures, significantly lower threshold values are shown for the SFH built in 2016. The corresponding threshold price for the investigated MFHs, except for the oldest one, is 0.13 €/kWh$_{H2}$ (percentage ratio H_2/elec.-price of 42%) for 2020 and 0.17 €/kWh$_{H2}$ (percentage ratio H_2/elec.-price of 55%) for 2050, mainly triggered by fuel cell operation. We identify an economically-viable hydrogen price of up to 0.11 €/kWh$_{H2}$ (percentage ratio H_2/elec.-price of 35%) to heat all of the examined buildings with hydrogen in 2050 at an electricity price of 0.31 €/kWh.

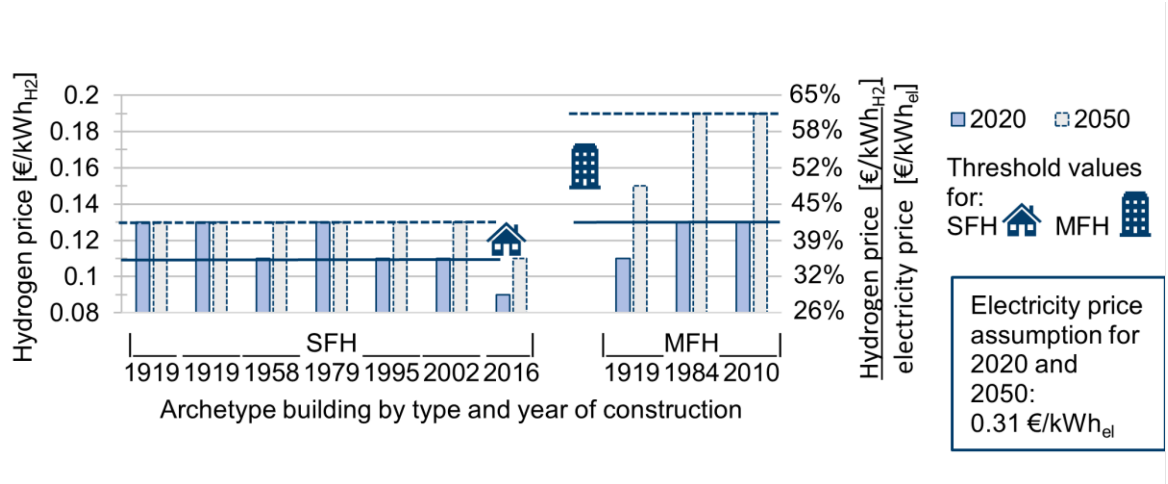

Figure 15. Threshold value of hydrogen end use price at which the use of hydrogen becomes economically-viable (left); threshold hydrogen price in relation to a fixed electricity price (right). Based on a hydrogen price sensitivity analysis for SFHs and MFHs for a fixed electricity supply price.

For 2020, no economically-viable use of hydrogen in German residential buildings can be derived from the results in a predicted residential consumer price range of 0.2–0.31 €/kWh$_{H2}$ (percentage ratio H_2/elec.-price of 65 to 100%) for green hydrogen from Germany. All identified threshold prices for 2020 lie below this range. For 2050, the consumer price predicted in [39] ranges between 0.17 and 0.24 €/kWh$_{H2}$ (percentage ratio H_2/elec.-price of 55 to 77%). At this price, hydrogen could only be economically used in the MFHs from 1984 and 2010. However, according to [34], the production costs of green hydrogen could decrease significantly more, which would result in a hydrogen price for residential buildings of 0.12 €/kWh$_{H2}$ (percentage ratio H_2/elec.-price of 39%). For this price, all buildings examined, except the SFH built in 2016, could use hydrogen in an economically-viable way for their energy systems under the assumption of an electricity price of 0.31 €/kWh$_{el}$.
With one exception, the threshold values for older SFHs do not differ between either target year because hydrogen boilers are cost-optimal in combination with heat pumps, which purchase electricity at 70% of the regular cost of electricity. We do not assume an increase in either the efficiency or costs of hydrogen boilers. In contrast, threshold values differ for both target years if younger SFHs and MFHs are considered. This is because fuel cell CHPs are used in combination with hydrogen boilers and heat pumps.

For MFHs, fuel cells can be economically-viable in 2050, as a significant price reduction can be expected. This is due to proportionally higher electricity demand compared to SFHs in combination with limited PV capacity, and so the cogeneration of heat and power makes fuel cell CHPs profitable, regarding the lower hydrogen price assumed for 2050. This analysis reveals that the hydrogen price is not necessarily prohibitive for the use of hydrogen in buildings in 2050. Much more important is the question of how to distribute, at least initially, small amounts of hydrogen, which must be supported by political institutions.

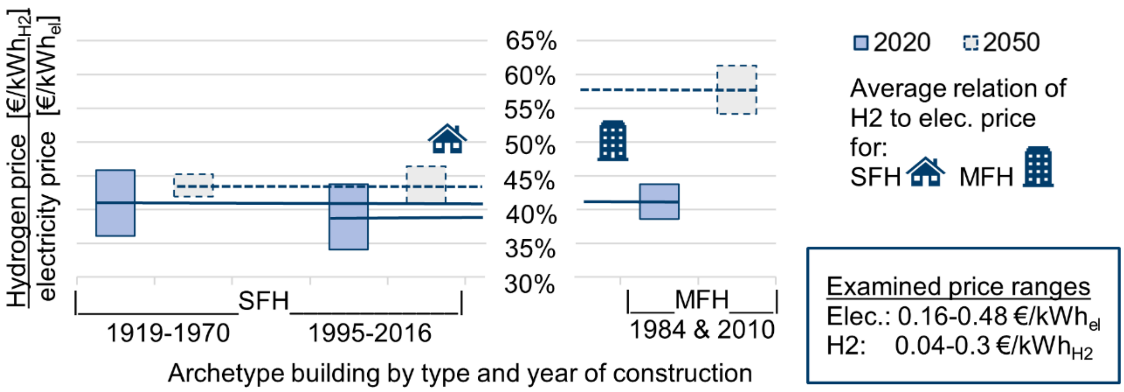

Figure 16. Threshold values for hydrogen end use price relative to electricity price at which the use of hydrogen becomes economically-viable. Based on a hydrogen price sensitivity analysis for SFHs and MFHs for a variable electricity supply price.

Figure 16 shows the relation of the hydrogen price to the price of electricity, which was determined with the sensitivities of both prices. In the areas shown, the use of hydrogen begins to make economic sense for the buildings investigated. They range from 34 to 61%, based on our assumptions for the technological and economic parameters for both target years. If the individual building groups are considered for the year 2050, a relationship of the hydrogen to electricity price of around 44% can be determined for SFHs. For MFHs, this relation is around 58%, which is favored by the use of CHP. The higher ratio of the hydrogen price in relation to the electricity price indicates that hydrogen could be more expensive compared to the electricity price than with a lower ratio for an economically-viable use of hydrogen. Our determined percentage ratios are higher than the corresponding ratio for natural gas in Germany for 2020, lying at 21% due to the high electricity and low natural gas prices.

Renovation measures are made cost-optimal by significantly reducing the heat demand if the hydrogen price is high and hydrogen-fueled technologies are not economical. In this regard, they compete with high-performance heat pumps. Our analysis of the buildings' cost-optimal technology pathways and renovation measures shows that buildings built in 1990 and earlier are renovated based on our assumptions for 2020 and 2050, except for the MFH built in 1984 for our 2050 assumptions.

In the building sector as it currently stands, heat pumps are a well-functioning alternative to hydrogen. They are significantly more efficient than heating with green hydrogen-fueled boilers, which significantly reduces necessary primary energy generation [29]. Despite these clear disadvantages in terms of efficiency, our analysis show that a comparatively low hydrogen price can compensate for the advantages of heat pumps from the economic perspective of a building owner.

Looking at the bigger picture, a key argument for the use of hydrogen in general is its ability to provide flexibility in the process of decarbonizing multiple sectors [9]. In general, hydrogen is seen to present a major opportunity for the decarbonization of the industrial and transportation sectors due to its high energy density and low GHG emissions, and its role in the building sector is considered to be minor [21]. However, it can be observed that due to an increased presence in the industrial and transport sectors, regional systems are emerging that could make hydrogen usable in buildings. Predestined for this are areas in northern Germany, where electrolysis is performed using surplus electricity from wind power, as well as in the Ruhr area, where industrial demand is particularly high. Finally, electrification of the building heat supply might not always be possible due to space or noise restrictions or heritage building preservation laws. Here, the heat supply with hydrogen can represent an alternative to heat pumps.

5 Conclusions

This bottom-up study investigated the role of hydrogen in the climate-neutral energy supply, considering renovation measures in German residential buildings in comparison to electricity-based systems, based on a selection of archetype buildings for single- and multi-family houses of different construction years. The results show that for the assumed costs of hydrogen of 0.25 €/kWh_{H2} for 2020 and 0.2 €/kWh_{H2} for 2050, heat pumps were used for heating in all of the buildings studied and hydrogen plays no role. These results are congruent with those of most other studies on this topic [16]–[19]. We performed sensitivity analyses that resulted in threshold values of the hydrogen price for its use in residential buildings. The thresholds depict the break-even price at which hydrogen supply technology becomes economically-viable for end users. We identified an end-use price threshold for the supply of hydrogen of 0.13 €/kWh_{H2} (percentage ratio H_2/elec.-price of 42%) for single-family houses and 0.17 €/kWh_{H2} (percentage ratio H_2/elec.-price of 55%) for multi-family houses at an electricity supply price of 0.31 €/kWh. In general, for percentage ratios of the hydrogen price in relation to the price of electricity of between 34 and 61%, the use of hydrogen in the residential sector starts making sense economically. Older SFHs select hydrogen boilers in combination with heat pumps to serve a high heat demand. Modern SFHs, as well as MFHs with lower specific heat demands, also profit from fuel cells to serve their electricity demand.

For the case of green hydrogen from renewable electricity, it is highly questionable whether it will be that much cheaper than direct electricity supply. As recognized in a similar form by Gerhardt et al, the economic usage of hydrogen in buildings is uncertain to unlikely [15].

In consequence, green hydrogen will most probably only play a role in buildings where heat pumps are not a technically feasible solution, or in dedicated regions with a high hydrogen demand density (in combination with the industrial and transportation sectors) where lower hydrogen supply prices can be realized.

Further research is needed on the topic of the future costs of green hydrogen for use in residential buildings, considering the costs of hydrogen distribution grids for the connection of buildings. Additionally, more detailed investigations could be useful with regard to the use of hybrid gas boiler/heat pump appliances, as at the time of writing this combination is being heavily promoted. The scope of this paper’s topic could be expanded in order to investigate the entire building stock in Germany, and to be able to make comprehensive qualitative as well as quantitative statements about the use of hydrogen in German residential buildings.

Acknowledgements
This work was funded by the German Federal Ministry of Education and Research as part of the research project, “LLEC: Living Lab Energy Campus – P2G++” (03SF0573).

Author contributions
K.K., P.S., and L.K. developed the research idea. K.K. and L.L. collected the techno-economic data. K.K. created the model. K.K. and L.L analyzed the data and interpreted the results. P.S., N.P., and L.K. participated in the discussion and data analysis. D.S. supervised the project. K.K. and L.L. wrote the manuscript. All authors contributed to discussions and the review and editing of the manuscript.

Competing interests
The authors have no competing interests to disclose.

Data availability
Data will be made available on request.

6 Appendices

Building year	Building type	TABULA Code	Living space (per house-hold) [m²]	Roof area [m²]	Roof type	House-holds	Residents per building (per houshold)
1919	SFH	DE.N.SFH.03.Gen. ReEx.001.001	303	214	Gabled	1	5
1919	TH	DE.N.TH.03.Gen. ReEx.001.001	113	50	Flat	1	5
1919	MFH	DE.N.MFH.03.Gen. ReEx.001.001	385 (64,17)	190	Gabled	6	18 (3)
1958	SFH	DE.N.SFH.05.Gen. ReEx.001.001	121	190	Gabled	1	5
1979	TH	DE.N.TH.07.Gen. ReEx.001.001	108	98	Flat	1	5
1984	MFH	DE.N.MFH.08.Gen. ReEx.001.001	778 (64,83)	249	Flat	12	36 (3)
1995	SFH	DE.N.SFH.09.Gen. ReEx.001.001	122	116	Gabled	1	5
2002	TH	DE.N.TH.10.Gen. ReEx.001.001	152	91	Gabled	1	5
2010	MFH	DE.N.MFH.11.Gen. ReEx.001.001	1,305	321	Flat	20	60 (3)
2016	SFH	DE.N.SFH.12.Gen. ReEx.001.001	187	132	Gabled	1	5

Table 5. Building parameters of the building selection **[30]**.

Building ID from TABULA [30]	No renovation (T^{sup}= 70 °C)	Level 1 renovation (T^{sup}=50 °C)		Level 2 renovation (T^{Sup}=35 °C)			
	Spec. heat. [kWh_{th}/m^2]	Cost [EUR]	Spec. heat. [kWh_{th}/m^2]	Cost [€]	Spec. heat. [kWh_{th}/m^2]	Hot Water [kWh_{th}/ person]	Elec. Appl. [kWh_{el}/ person]
DE.N.SFH.03	210.65	47,344	54.94	59,558	45.92	811.67	884.88
DE.N.TH.03	141.76	15,300	42.37	18,767	34.94	811.67	884.88
DE.N.MFH.03	191.41	57,186	45.86	71,165	37.10	794.85	767.12
DE.N.SFH.05	231.13	30,490	64.73	38,730	52.53	811.67	884.88
DE.N.TH.07	115.81	19,350	44.68	23,841	37.18	811.67	884.88
DE.N.MFH.08	102.45	116,41	40.33	144,011	32.61	913.92	875.97
DE.N.SFH.09	96.20	27,164	49.86	33,954	40.48	811.67	884.88
DE.N.TH.10	59.68	27,105	39.39	33,679	31.78	811.67	884.88
DE.N.MFH.11	51.84	171,32	36.55	211,933	30.62	926.82	1049.23
DE.N.SFH.12	61.22	37,436	47.52	46,840	40.33	811.67	884.88

Table 6. Renovation costs and specific heat demand for each building and all three renovation levels. Hot water demand and the demand of electric appliances is the same for all renovation levels for each building.

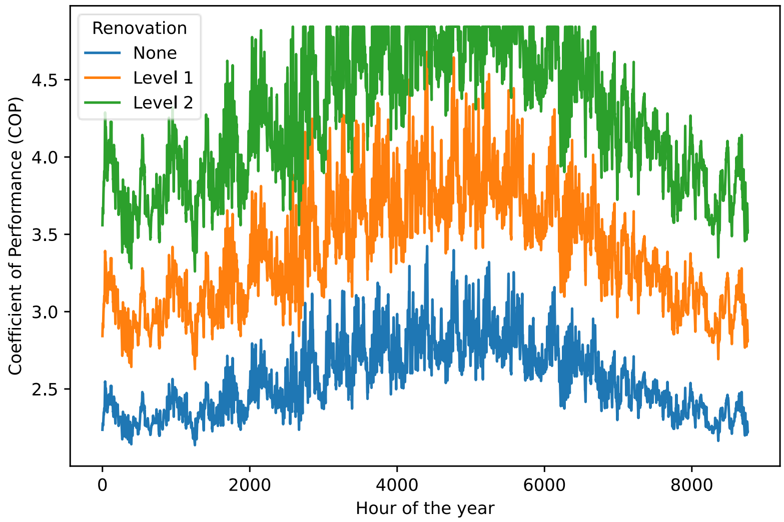

Figure 17. COP time series for each heat pump sub-component, calculated according to [50].

Building year	Building type	Reno-vation	Heating temp. [°C]	HP annual COP 2020	HP annual COP 2050	HP power [kW_{el}] 2020	HP power [kW_{el}] 2050	Heat generation [kWh_{th}] 2020	Heat generation [kWh_{th}] 2050
1919	SFH	None	70	2.37	2.38	8.68	11.15	60,607	60,819
		Level 1	50	3.01	3.03	2.84	4.26	14,176	13,851
		Level 2	35	3.73	3.80	2.27	3.56	11,575	11,152
1919	TH	None	70	2.35	2.35	3.95	2.95	13,152	13,189
		Level 1	50	2.91	2.98	1.84	3.28	2,804	2,466
		Level 2	35	3.59	3.71	2.78	2.78	1,862	1,734
1919	MFH	None	70	2.36	2.36	13.01	16.72	57,405	57,795
		Level 1	50	2.93	2.96	6.68	8.84	6,707	6,323
		Level 2	35	3.44	3.68	6.69	9.28	4,312	3,686
1958	SFH	None	70	2.37	2.37	4.53	6.18	24,960	25,119
		Level 1	50	3.00	3.01	3.11	3.11	5,384	5,249
		Level 2	35	3.70	3.77	2.73	2.73	4,004	3,862
1979	TH	None	70	2.35	2.35	2.77	4.35	9,729	9,813
		Level 1	50	2.95	2.98	2.77	2.77	2,637	2,492
		Level 2	35	3.58	3.71	2.79	2.80	1,918	1,772
1984	MFH	None	50	3.01	3.02	17.62	21.02	55,497	54,160
		Level 1	50	2.91	2.94	13.71	15.73	11,932	11,107
		Level 2	35	3.12	3.67	13.27	15.63	11,318	6,435
1995	SFH	None	50	2.99	3.02	2.30	4.15	9,396	8,983
		Level 1	50	2.95	2.99	2.01	3.51	4,023	3,720
		Level 2	35	3.46	3.74	1.77	2.92	3,181	2,673
2002	TH	None	50	3.00	3.01	3.30	3.30	6,629	6,486
		Level 1	50	2.97	2.99	3.14	3.15	3,821	3,666
		Level 2	35	3.65	3.73	2.95	2.96	2,726	2,605
2010	MFH	None	50	2.97	2.98	25.05	29.24	34,664	34,028
		Level 1	50	2.68	2.94	24.38	30.11	52,472	17,562
		Level 2	35	3.59	3.66	23.04	25.72	11,472	11,410
2016	SFH	None	35	3.77	3.80	3.73	3.73	8,898	8,756
		Level 1	35	3.67	3.78	1.98	3.42	6,694	6,336
		Level 2	35	3.55	3.77	2.02	3.35	5,860	5,037

Table 7. Heat pump data for the optimized buildings and their renovation levels, regarding heating temperature, the annual COP, the power and heat generation of the heat pumps.

	Electricity price [EUR/kWh]															
Hydrogen price [EUR/kWh]	**0.16**	**0.18**	**0.20**	**0.22**	**0.24**	**0.26**	**0.28**	**0.30**	**0.32**	**0.34**	**0.36**	**0.38**	**0.40**	**0.42**	**0.44**	**0.48**
0.04	2.47	2.54	2.6	2.65	2.70	2.72	2.73	2.74	2.73	2.69	2.62	2.56	2.49	2.42	2.34	2.15
0.06	2.78	2.85	2.91	2.96	3.01	3.05	3.09	3.11	3.12	3.08	3.04	3.00	2.96	2.91	2.87	2.78
0.08	3.07	3.13	3.19	3.24	3.29	3.33	3.36	3.38	3.41	3.38	3.34	3.30	3.26	3.22	3.18	3.10
0.10	3.09	3.25	3.40	3.52	3.56	3.60	3.62	3.65	3.67	3.67	3.63	3.60	3.56	3.52	3.48	3.41
0.12	3.09	3.25	3.40	3.54	3.63	3.69	3.75	3.81	3.83	3.85	3.87	3.88	3.85	3.81	3.78	3.70
0.14	3.09	3.25	3.40	3.54	3.63	3.69	3.75	3.82	3.88	3.94	4.00	4.02	4.03	4.01	3.98	3.92
0.16	3.09	3.25	3.40	3.54	3.63	3.69	3.75	3.82	3.88	3.94	4.00	4.06	4.12	4.16	4.14	4.09
0.18	3.09	3.25	3.40	3.54	3.63	3.69	3.75	3.82	3.88	3.94	4.00	4.06	4.12	4.18	4.24	4.25
0.20	3.09	3.25	3.40	3.54	3.63	3.69	3.75	3.82	3.88	3.94	4.00	4.06	4.12	4.18	4.24	4.36
0.22	3.09	3.25	3.40	3.54	3.63	3.69	3.75	3.82	3.88	3.94	4.00	4.06	4.12	4.18	4.24	4.36
0.24	3.09	3.25	3.40	3.54	3.63	3.69	3.75	3.82	3.88	3.94	4.00	4.06	4.12	4.18	4.24	4.36
0.26	3.09	3.25	3.40	3.54	3.63	3.69	3.75	3.82	3.88	3.94	4.00	4.06	4.12	4.18	4.24	4.36
0.28	3.09	3.25	3.40	3.54	3.63	3.69	3.75	3.82	3.88	3.94	4.00	4.06	4.12	4.18	4.24	4.36
0.30	3.09	3.25	3.40	3.54	3.63	3.69	3.75	3.82	3.88	3.94	4.00	4.06	4.12	4.18	4.24	4.36

Table 8. Total annualized cost of energy supply in kEUR/a for combinations of supply prices for electricity and hydrogen for a typical terraced single-family house built in 1979 (DE.N.TH.07).

	Electricity price [EUR/kWh]															
Hydrogen price [EUR/kWh]	**0.16**	**0.18**	**0.20**	**0.22**	**0.24**	**0.26**	**0.28**	**0.30**	**0.32**	**0.34**	**0.36**	**0.38**	**0.40**	**0.42**	**0.44**	**0.48**
0.04	11.38	11.57	11.7	11.79	11.86	11.91	11.93	11.93	11.88	11.81	11.72	11.61	11.43	11.2	10.96	10.44
0.06	13.62	14.01	14.25	14.39	14.48	14.54	14.56	14.55	14.52	14.47	14.42	14.36	14.30	14.24	14.17	14.01
0.08	15.28	15.86	16.24	16.56	16.82	16.96	17.02	17.06	17.07	17.07	17.04	17.00	16.95	16.89	16.84	16.68
0.10	15.41	16.79	17.83	18.34	18.69	18.99	19.24	19.41	19.52	19.56	19.58	19.58	19.56	19.52	19.45	19.29
0.12	15.41	16.79	18.17	19.55	20.31	20.77	21.11	21.41	21.66	21.84	21.97	22.06	22.07	22.03	21.97	21.84
0.14	15.41	16.79	18.17	19.55	20.93	22.14	22.77	23.2	23.54	23.84	24.09	24.27	24.35	24.39	24.40	24.33
0.16	15.41	16.79	18.17	19.55	20.93	22.31	23.69	24.64	25.22	25.63	25.96	26.24	26.41	26.53	26.60	26.68
0.18	15.41	16.79	18.17	19.55	20.93	22.31	23.69	25.08	26.32	27.13	27.66	28.02	28.21	28.34	28.43	28.57
0.20	15.41	16.79	18.17	19.55	20.93	22.31	23.69	25.08	26.32	27.43	28.51	29.13	29.50	29.76	29.94	30.16
0.22	15.41	16.79	18.17	19.55	20.93	22.31	23.69	25.08	26.32	27.43	28.53	29.64	30.43	30.88	31.22	31.64
0.24	15.41	16.79	18.17	19.55	20.93	22.31	23.69	25.08	26.32	27.43	28.53	29.64	30.71	31.69	32.21	32.91
0.26	15.41	16.79	18.17	19.55	20.93	22.31	23.69	25.08	26.32	27.43	28.53	29.64	30.71	31.71	32.72	33.93
0.28	15.41	16.79	18.17	19.55	20.93	22.31	23.69	25.08	26.32	27.43	28.53	29.64	30.71	31.71	32.72	34.68
0.30	15.41	16.79	18.17	19.55	20.93	22.31	23.69	25.08	26.32	27.43	28.53	29.64	30.71	31.71	32.72	34.68

Table 9. Total annualized cost of energy supply in kEUR/a for combinations of supply prices for electricity and hydrogen for a typical multi-family house built in 1984 with 12 housholds(DE.N.MFH.08).

Literature

[1] Presse- und Informationsamt der Bundesregierung, “Klimaschutzgesetz 2021 - Generationenvertrag für das Klima.” https://www.bundesregierung.de/breg-de/themen/klimaschutz/klimaschutzgesetz-2021-1913672 (accessed Jun. 17, 2021).

[2] C. Senkpiel, “Bericht zur Vorjahresschätzung der deutschen Treibhausgasemissionen für das Jahr 2020,” 2020. Accessed: Aug. 24, 2021. [Online]. Available: https://expertenrat-klima.de/content/uploads/2021/04/210415_Bericht_Expertenrat_Klimafragen_2021.pdf

[3] Bundesministerium für Wirtschaft und Energie, “Die nationale Wasserstoffstrategie.” https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/die-nationale-wasserstoffstrategie.pdf?__blob=publicationFile&v=20 (accessed Jun. 17, 2021).

[4] Cadent and Northern Gas Networks, “HyDeploy Project - Fourth Project Progress Report,” Dec. 2020. https://hydeploy.co.uk/app/uploads/2018/02/HYDEPLOY-FOURTH-OFGEM-PPR.pdf (accessed Jul. 21, 2021).

[5] Netze BW GmbH, “Netzinnovationen - Wasserstoff-Insel,” *Netzinnovationen - Wasserstoff-Insel - Netze BW GmbH*, 2021. https://www.netze-bw.de/unsernetz/netzinnovationen/wasserstoff-insel (accessed Aug. 24, 2021).

[6] J. Bard, N. Gerhardt, P. Selzam, M. Beil, D. M. Wiemer, and M. Buddensiek, “THE LIMITATIONS OF HYDROGEN BLENDING IN THE EUROPEAN GAS GRID,” p. 50.

[7] Northern Gas Networks UK, “H21 project website.” https://h21.green/ (accessed Jul. 21, 2021).

[8] Hydrogen Council, “Path to hydrogencompetitiveness - A cost perspective,” Jan. 2020. [Online]. Available: https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

[9] International Renewable Energy Agency, “Making Green Hydrogen a Cost-Competitive Climate Solution.” https://www.irena.org/newsroom/pressreleases/2020/Dec/Making-Green-Hydrogen-a-Cost-Competitive-Climate-Solution (accessed Jul. 29, 2021).

[10] *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings*, vol. OJ L. 2010. Accessed: Jul. 20, 2021. [Online]. Available: http://data.europa.eu/eli/dir/2010/31/oj/eng

[11] N. P. Brandon and Z. Kurban, “Clean energy and the hydrogen economy,” *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.*, vol. 375, no. 2098, p. 20160400, Jul. 2017, doi: 10.1098/rsta.2016.0400.

[12] European Commission, “A hydrogen strategy for a climate-neutral Europe,” European Commission, Brussels, Jul. 2020. Accessed: Jul. 23, 2021. [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

[13] Fuel Cells and Hydrogen 2 Joint Undertaking, “Hydrogen roadmap Europe: a sustainable pathway for the European energy transition,” LU: Publications Office, 2019. [Online]. Available: https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf

[14] S. Cerniauskas, A. Jose Chavez Junco, T. Grube, M. Robinius, and D. Stolten, “Options of natural gas pipeline reassignment for hydrogen: Cost assessment for a Germany case study,” *Int. J. Hydrog. Energy*, vol. 45, no. 21, pp. 12095–12107, Apr. 2020, doi: 10.1016/j.ijhydene.2020.02.121.

[15] N. Gerhardt, J. Bard, R. Schmitz, M. Beil, M. Pfennig, and D. T. Kneiske, “HYDROGEN IN THE ENERGY SYSTEM OF THE FUTURE: FOCUS ON HEAT IN BUILDINGS,” p. 46.

[16] P. Gerbert *et al.*, “Klimapfade für Deutschland,” Bundesverband der Deutschen Industrie e.V. (BDI), 2018.

[17] Deutsche Energie-Agentur GmbH (dena), “dena-Leitstudie Integrierte Energiewende,” 2018. [Online]. Available: https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9262_dena-Leitstudie_Integrierte_Energiewende_Ergebnisbericht.pdf

[18] Prognos AG, Öko-Institut e.V., and Wuppertal Institut für Klima, Umwelt, Energie gGmbH, “Klimaneutrales Deutschland,” Agora Energiewende, 2020. [Online]. Available: https://static.agora-energiewende.de/fileadmin/Projekte/2020/2020_10_KNDE/A-EW_195_KNDE_WEB.pdf

[19] Umweltbundesamt (UBA), “Wege in eine ressourcenschonende Treibhausgasneutralität,” 2019. [Online]. Available: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/rescue_studie_cc_36-2019_wege_in_eine_ressourcenschonende_treibhausgasneutralitaet_auflage2_juni-2021.pdf
[20] E. S. Hanley, J. Deane, and B. Ó. Gallachóir, “The role of hydrogen in low carbon energy futures–A review of existing perspectives,” *Renew. Sustain. Energy Rev.*, vol. 82, pp. 3027–3045, Feb. 2018, doi: 10.1016/j.rser.2017.10.034.
[21] C. J. Quarton *et al.*, “The curious case of the conflicting roles of hydrogen in global energy scenarios,” *Sustain. Energy Fuels*, vol. 4, no. 1, pp. 80–95, 2020, doi: 10.1039/C9SE00833K.
[22] D. D. Bothe and D. M. Janssen, “Der Wert von Wasserstoff im Wärmemarkt,” p. 63, 2021.
[23] F. Ueckerdt *et al.*, “Kurzdossier: Durchstarten trotz Unsicherheiten - Eckpunkte einer anpassungsfähigen Wasserstoffstrategie | Ariadne.” https://ariadneprojekt.de/publikation/eckpunkte-einer-anpassungsfaehigen-wasserstoffstrategie/ (accessed Jul. 11, 2022).
[24] F. Schiro, A. Stoppato, and A. Benato, “Modelling and analyzing the impact of hydrogen enriched natural gas on domestic gas boilers in a decarbonization perspective,” *Carbon Resour. Convers.*, vol. 3, pp. 122–129, Jan. 2020, doi: 10.1016/j.crcon.2020.08.001.
[25] Bosch Thermotechnology Ltd., “Hydrogen Boiler | Worcester Bosch.” https://www.worcester-bosch.co.uk/hydrogen (accessed Jul. 23, 2021).
[26] I. Staffell *et al.*, “The role of hydrogen and fuel cells in the global energy system,” *Energy Environ. Sci.*, vol. 12, no. 2, pp. 463–491, Feb. 2019, doi: 10.1039/C8EE01157E.
[27] FuelCellsWorks, “Netherlands: Apartment Complex In Rotterdam Municipality Rozenburg Heated With Hydrogen - FuelCellsWorks.” https://fuelcellsworks.com/news/netherlands-apartment-complex-in-rotterdam-municipality-rozenburg-heated-with-hydrogen/ (accessed Jul. 22, 2021).
[28] B. Nastasi, “Renewable Hydrogen Potential for Low-carbon Retrofit of the Building Stocks,” *Energy Procedia*, vol. 82, pp. 944–949, Dec. 2015, doi: 10.1016/j.egypro.2015.11.847.
[29] LETI, “Hydrogen: A decarbonisation route for heat in buildings?,” London Energy Transformation Initiative, 2021. Accessed: Aug. 23, 2021. [Online]. Available: https://b80d7a04-1c28-45e2-b904-e0715cface93.filesusr.com/ugd/252d09_54035c0c27684afca52c7634709b86ec.pdf
[30] Institut für Wohnen und Umwelt, “EPISCOPE and TABULA Website.” https://episcope.eu/iee-project/ (accessed Jun. 24, 2021).
[31] T. Schütz, L. Schiffer, H. Harb, M. Fuchs, and D. Müller, “Optimal design of energy conversion units and envelopes for residential building retrofits using a comprehensive MILP model,” *Appl. Energy*, no. 185, pp. 1–15, Jan. 2017, doi: https://doi.org/10.1016/j.apenergy.2016.10.049.
[32] DWD, “Testreferenzjahre (TRY) 2011.” https://www.dwd.de/DE/leistungen/testreferenzjahre/testreferenzjahre.html (accessed Jun. 25, 2021).
[33] K. Knosala *et al.*, “Hybrid Hydrogen Home Storage for Decentralized Energy Autonomy,” *Int. J. Hydrog. Energy*, vol. 46, no. 42, pp. 21748–21763, Jun. 2021, doi: 10.1016/j.ijhydene.2021.04.036.
[34] IRENA, “Hydrogen: A renewable energy perspective,” International Renewable Energy Agency, Abu Dhabi, 2019.
[35] U.S. Department of Energy, “DOE Technical Targets for Hydrogen Production from Electrolysis,” *Energy.gov*, 2020. https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-production-electrolysis (accessed Aug. 20, 2021).
[36] Bundesnetzagentur, “Netzentgelt (Strom und Gas),” 2021. https://www.bundesnetzagentur.de/SharedDocs/A_Z/N/Netzentgelt.html (accessed Aug. 23, 2021).
[37] S. Bukold, “Gaspreise 2016/17,” EnergyComment, 2016. Accessed: Aug. 25, 2021. [Online]. Available: https://baerbel-hoehn.de/archiv/fileadmin/media/MdB/baerbelhoehn_de/www_baerbelhoehn_de/Gaspreise-Gruene-Bukold_2016.pdf

[38] BMWI, “Staatlich veranlasste Bestandteile des Gaspreises,” 2021. https://www.bmwi.de/Redaktion/DE/Artikel/Energie/gaspreise-bestandteile-staatlich.html (accessed Aug. 25, 2021).
[39] P. Heuser, “Weltweite Infrastruktur zur Wasserstoffbereitstellung auf Basis erneuerbarer Energien,” Forschungszentrum Jülich GmbH Znetralbibliothek, Verlag, 2021. Accessed: Aug. 20, 2021. [Online]. Available: https://juser.fz-juelich.de/record/893099
[40] European Commission - Eurostat, “Gaspreise nach Art des Benutzers.” https://ec.europa.eu/eurostat/databrowser/view/ten00118/default/map?lang=de (accessed Mar. 04, 2022).
[41] European Commission - Eurostat, “Strompreise nach Art des Benutzers.” https://ec.europa.eu/eurostat/databrowser/view/ten00117/default/table?lang=de (accessed Mar. 04, 2022).
[42] “Stromtarife für Wärmepumpen: Schnell zum günstigsten Vertrag - Finanztip.” https://www.finanztip.de/stromtarife/waermepumpe/ (accessed Jun. 30, 2022).
[43] K. Matuszny, T. N. Borhani, S. A. Nabavi, and D. P. Hanak, “Integration of solid-oxide fuel cells and absorption refrigeration for efficient combined cooling, heat and power production,” *Clean Energy*, vol. 4, no. 4, pp. 328–348, Dec. 2020, doi: 10.1093/ce/zkaa019.
[44] European Energy Exchange AG, “KWK Index.” https://www.eex.com/de/marktdaten/strom/kwk-index (accessed Jan. 21, 2022).
[45] D. Powell, “Focus on Blue Hydrogen (August 2020).” GaffneyCline. [Online]. Available: https://www.gaffneycline.com/sites/g/files/cozyhq681/files/2020-08/Focus%20on%20Blue%20Hydrogen.pdf
[46] Prognos, “Eigenversorgung aus Solaranlagen. Das Potenzial für Photovoltaik-Speicher-Systeme in Ein- und Zweifamilienhäusern, Landwirtschaft sowie im Lebensmittelhandel. Analyse im Auftrag von Agora Energiewende,” Prognos, 2016. [Online]. Available: https://www.prognos.com/sites/default/files/2021-01/20161011_prognos_agora_eigenversorgung_pv_web-02.pdf
[47] L. Kotzur *et al.*, “Bottom-up energy supply optimization of a national building stock,” *Energy Build.*, vol. 209, p. 109667, Feb. 2020, doi: 10.1016/j.enbuild.2019.109667.
[48] L. Kotzur, D. Stolten, and H.-J. Wagner, “Future grid load of the residential building sector,” Forschungszentrum Jülich GmbH, Zentralbibliothek, Verlag, 2018. doi: 10.18154/RWTH-2018-231872.
[49] Viessmann Climate Solutions SE, “Datenblatt Vitovalor PT2,” *Viessmann*, Aug. 17, 2021. https://www.viessmann.de/content/dam/vi-brands/DE/Produkte/Kraft-Waerme-Kopplung/Brennstoffzelle/Vitovalor-PT2/DB-6020301_Vitovalor_PT2.pdf/_jcr_content/renditions/original.media_file.download_attachment.file/DB-6020301_Vitovalor_PT2.pdf (accessed Aug. 26, 2021).
[50] K. B. Lindberg, D. Fischer, G. Doorman, M. Korpas, and I. Sartori, “Cost-optimal energy system design in Zero Energy Buildings with resulting grid impact: A case study of a German multi-family house,” *Energy Build.*, no. 127, pp. 830–845, Sep. 2016, doi: https://doi.org/10.1016/j.enbuild.2016.05.063.
[51] D. Sauer *et al.*, *Energiespeicher - Technologiesteckbrief zur Analyse „Flexibilitätskonzepte für die Stromversorgung 2050“*. 2015. doi: 10.13140/RG.2.1.1478.4409.
[52] L. Welder, D. S. Ryberg, L. Kotzur, T. Grube, M. Robinius, and D. Stolten, “Spatio-temporal optimization of a future energy system for power-to-hydrogen applications in Germany,” *Energy*, vol. 158, pp. 1130–1149, Sep. 2018, doi: 10.1016/j.energy.2018.05.059.
[53] European Commission, “EUR-Lex - COMMISSION DELEGATED REGULATION (EU) No 244/2012,” 2012. https://eur-lex.europa.eu/legal-content/GA/TXT/?uri=CELEX%3A32012R0244 (accessed Aug. 11, 2021).