The role of hydrogen in German residential buildings

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Abstract

As fossil-fueled heating in the building sector is responsible for 16 % of Germanys total CO2 emissions, it is of great importance to use climate-neutral alternatives for the decarbonization of this sector. Options for the climate-neutral heating of buildings include electricity or hydrogen as energy carriers, both explicitly considered by German policy. In this paper, bottom-up studies are conducted to investigate the role of hydrogen for the climate-neutral energy supply of ten selected residential buildings in comparison to electricity-based systems. Based on a selection of as different typical buildings as possible for single- (SFH) and multi-family houses (MFH) of different construction years, demand profiles are simulated for each building and the respective cost-optimal supply system is determined. For the construction of this system, the electricity-based technologies available are electric heater and heat pump as well as the hydrogen-based technologies hydrogen boiler and fuel cell combined heat and power (CHP) system. Based on the results of the optimization, sensitivity analyses are performed. These analyses aim to identify threshold values of the hydrogen price for the use of hydrogen in building energy systems as well as to make the quantities of hydrogen consumed visible.
The identified threshold values show the significant role of hydrogen-operated CHP in MFH if the hydrogen price reaches 0.17 €/kWh_{H2} in 2050 at an electricity price of 0.31 €/kWh_{el}. So, hydrogen-based energy systems represent an economically viable alternative to electricity-based systems with heat pumps. We identify electricity to hydrogen price ratios for the economically viable use of hydrogen in the examined buildings that range from 1.67 to 2.82. According to these ratios, the economically reasonable use of hydrogen in buildings can be derived. For the individual building groups for the year 2050, a ratio of 2.5 can be determined for SFH and 1.8 for MFH, that is favored by the use of CHP which also supplies electricity to the buildings. However, the role hydrogen will finally play in German residential buildings in the future depends to a large extent on political decisions on distribution issues and price signals.

Keywords

Hydrogen, residential buildings, heat supply, renovation, price sensitivity, bottom-up

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Highlights

- Hydrogen can play a significant role in German residential buildings in the future
- Price of hydrogen does not appear to be a showstopper
- An electricity to hydrogen price ratio of 2.5 for SFH and 1.8 for MFH makes hydrogen economically viable in the buildings considered for 2050
- Hydrogen can be economically viable in the future compared to heat pumps
- Choice between hydrogen and heat pumps can be made via price signals by policy
- It is crucial where the initially small quantities of hydrogen are to be used

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 one of these sectors, buildings account for 16% (as of 2020) of Germany's total CO2 emissions due to the use of fuels for heating and hot water generation [2]. In order 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 process that is already taking place [3]. One way to use hydrogen in the building sector is by repurposing existing infrastructure, such as conversion of the natural gas grid and building energy system devices to be able to utilize hydrogen. The steps of such a transformation are outlined in Figure 1. The first phase would comprise the transition from the state-of-the-art natural gas grid to a demonstration grid operating with a blend of hydrogen. Such a project is currently being carried out by the Cadent and Northern Gas Networks in the UK: HyDeploy expects to demonstrate technical feasibility by blending 20% hydrogen into a distribution grid by 2023 [4]. A similar project is conducted by Netze BW in Germany, who plan to demonstrate a blend of even up to 30 % hydrogen into the gas grid until 2023 [5]. After this, the final transitional step would be a gas infrastructure that runs exclusively on hydrogen which, e.g., is the goal of the H21 project, being led by Northern Gas Networks in the UK [6]. This new hydrogen infrastructure could consist of actual new construction or the repurposing of the existing natural gas infrastructure. Decentralized generation and the storage and use of hydrogen is also possible and would even enable hydrogen supply for buildings where there was no existing gas grid, or for which new construction would be too expensive.

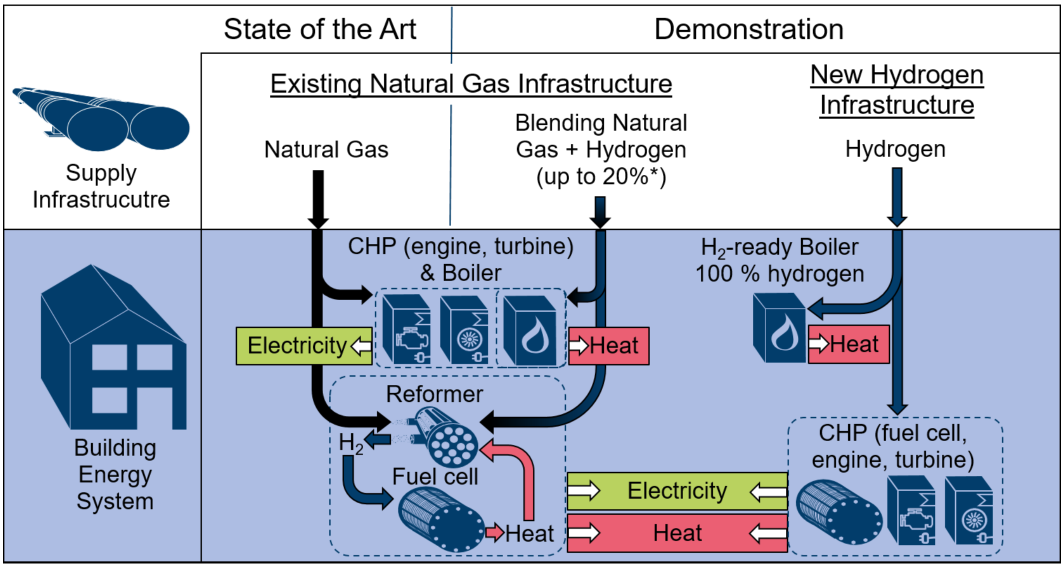

Figure 1. Transition of the supply infrastructure and building energy systems from natural gas to hydrogen operation.

The role 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. On 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 shows a threshold price, whereby the use of hydrogen becomes the more economical alternative, of 4.54 €/kg_{H2} for renovated buildings and 2.52 €/kg_{H2} for new ones [7]. The cost of climate-friendly hydrogen depends on how it is produced. According to a report by the International Renewable Energy Agency, green hydrogen produced by electrolysis powered by renewably-generated electricity costs more than 5 €/kg_{H2} in 2020. That is two to three times as high as blue hydrogen, which is produced from fossil natural gas, including storage of the resulting CO_2 [8].

1.1 Literature review

As a flexible clean energy carrier, hydrogen could be a key element in the decarbonization of the building, transport, commercial, and industrial sectors [9]. In 2010, the European Parliament issued a directive on this topic, specifying that all new buildings must be nearly zero-energy by 2021. This new standard prescribes low energy demand among buildings, which is to be covered to a substantial extent by renewable sources [10]. 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 reached by the year 2050 [11]. This European hydrogen roadmap sees hydrogen as a decisive factor for heat supply in the building sector, in the most ambitious scenario for 2050. The sector is projected to account for 26% of hydrogen demand, which corresponds to 579 TWh_{H2} [12]. In Germany, the National Hydrogen Strategy also includes infrastructure for hydrogen generation, transport, storage, and usage that is interconnected nationally and at the European level. Amongst other things, it is based on existing natural gas grids that must be adapted to the particular physical and chemical properties of hydrogen in order to allow for its use in heating residential buildings [3], [13].

As the importance of hydrogen is increasingly recognized by researchers and policymakers alike, energy scenarios are unclear regarding the role of hydrogen 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 [14]. 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 against the use of hydrogen. They advocate the extensive use of heat pumps, even without any renovation of existing buildings, and thereby the direct use of electricity. In other studies, hydrogen has also played no role in the energy supply of buildings. Here, heat pumps and district heating are preferred for heat supply [15]–[18]. Hanley et al. reviewed the role of hydrogen across different energy scenarios with different areas of focus [19]. They conclude 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 their review paper, Quarton et al. investigate the inconsistent role that hydrogen currently plays in global energy scenarios [20]. 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 of hydrogen for the heating of buildings and a great opportunity in the industrial and transportation sectors. Regarding 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 energy system transformation. They identify a need for government targets and policy measures to develop hydrogen infrastructure and production at scale [9].
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 in order to achieve the same thermal load due to the lower heating value of hydrogen. Also, if the hydrogen content exceeds 20%, the burner must be redesigned to prevent the risk of unintended ignition and flashbacks [21]. Worcester-Bosch, a leading manufacturer of gas boilers, expects that hydrogen-ready boilers will have the same costs as current natural gas ones [22]. In addition to purchasing new, hydrogen-ready boilers, one option is to retrofit existing natural gas units with new burner tips and controls. Nationwide conversion measures have already been implemented in the conversion from town to natural gas, which can serve as an example [23]. As a field test for hydrogen heating, an apartment complex in the Netherlands was heated using 100% hydrogen, using hydrogen-ready boilers. The project aims to demonstrate heating using pure hydrogen and its distribution over an existing natural gas pipeline [24]. Staffell et al. discuss systems that consume hydrogen and provide combined heat and power (CHP) as an alternative to hydrogen-ready boilers [23]. 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 (SOFC) are typically chosen, and typically feature 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 has halved to about 8,400 €/kW$_{el}$, and the lifetime has increased, due to their diffusion, especially in Japan and Europe [23]. 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% hydrogen in natural gas [25].
Since hydrogen cannot yet be obtained for use in residential buildings, a theoretical price is derived from literature values for the years 2020 and 2050. Regionally produced hydrogen is assumed for 2020 and imported hydrogen for 2050. Production costs of green hydrogen for the year 2019 range from 2.8 to 6.2 €/kg$_{H2}$, according to a report of the International Renewable Energy Agency (IRENA) [26]. 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 a regional production, the U. S. Department of Energy assumes a transport price around 1.5 €/kg$_{H2}$ [27]. So, production of green hydrogen and its regional transport result in 4.3 to 7.7 €/kg$_{H2}$ or 0.13 to 0.23 €/kg$_{H2}$, regarding the lower heating value of hydrogen. For the distribution to residential buildings in Germany, an average network fee of 0.0156 €/kWh$_{H2}$ is charged by the network operators in the year 2020 [28]. The

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gas supplier also charges costs for distribution and its margin in the amount of approximately 0.02 €/kWh$_{H2}$ [29]. In addition, a sales tax in the amount of 19 % applies, while a gas tax, which is primarily intended to serve climate policy goals, is not considered for green hydrogen due to its climate neutrality [30]. Thus, the theoretical costs for regional produced green hydrogen for the use in German residential buildings in the year 2020 are between 0.2 and 0.31 €/kWh$_{H2}$. For the year 2050, the import of global produced hydrogen is assumed in this paper. According to Heuser, global costs for green hydrogen at the export harbor will range from 3 to 5 €/kg$_{H2}$ [31]. In addition, Heuser expects transport via ship and liquid organic hydrogen carriers (LOHC) to cost 0.35 €/kg$_{H2}$. For the transport within Germany, an existing network is assumed that causes insignificant additional 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 the use in German residential buildings, according to published data. According to the aforementioned report of IRENA, hydrogen production costs could reach 0.85 €/kg$_{H2}$ in 2050 [26]. Together with the pure supply costs in the exporting country, which according to [31] amount to about 1 €/kg$_{H2}$, and 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.

An indicator to show the difference between electricity and gas prices is provided by the electricity to gas price ratio. This ratio describes the quotient of electricity and gas prices as they can be determined at the respective point in time on the basis of market prices for both energy carriers. For natural gas in Europe in 2020, this ratio ranges from 1.2 in the Netherlands to 4.7 in Belgium [32]. Germany has the second highest ratio with 4.2 and the European average is at around 2.2 in 2020. The larger the electricity to gas price ratio, the more the electricity price is above the gas price per kWh.

A big disadvantage of heating with hydrogen, compared to the use of heat pumps, is the low efficiency. The London Energy Transformation Initiative presented an independent report in February 2021, in which they compared two routes of heating buildings: Using green hydrogen for boilers or electricity with heat pumps [33]. 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 [33].

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 [20]. Thus, the aim of this paper is to provide a detailed techno-economic analysis of ten selected buildings that are typical of German building stock. This analysis compares hydrogen-based building energy systems with those based on renewable electricity for the target years 2020 and 2050. 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, 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 in order 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 for single systems using a mixed-integer linear program (MILP) optimization model. For this goal, we proceeded as shown in Figure 2. We selected 10 buildings built between 1919 and 2016 that substantially differed 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 input 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 cost-optimal energy system for each building was determined by drawing on the offered supply systems.

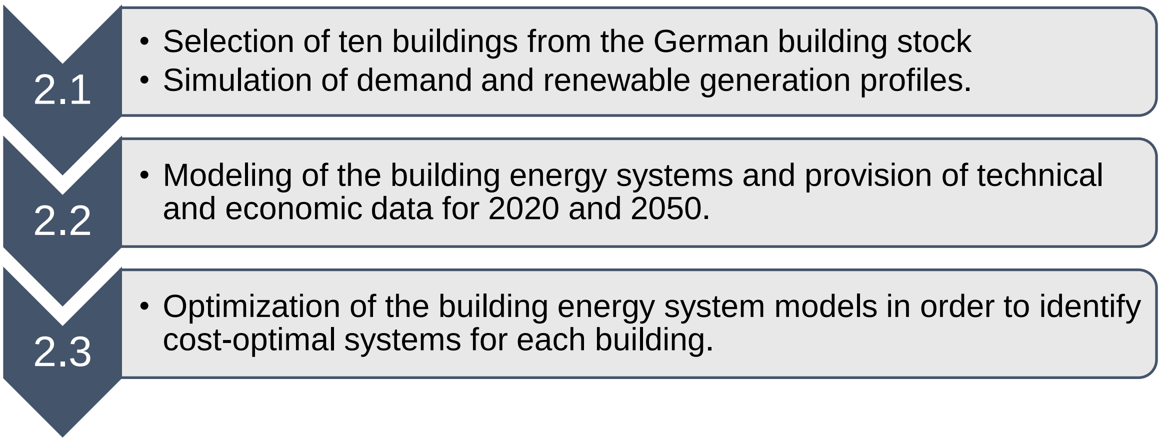

Figure 2. Flowchart depicting the methodological procedures followed in this study.

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

The TABULA database contains the physical building characteristics of archetype buildings from different construction years that are representative of the entire German building stock [34]. 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, because we conduct extensive sensitivity analyses, we limit our selection to ten of these archetypal buildings with construction years between 1919 and 2016 and analyze their cost-optimal energy systems. 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 with 6, 12, and 20 households. ABs were not considered due to the especially long computational times their analysis would require. Basic building parameters for each selected building are presented in Table 5.
Optimization of the building energy systems has the goal of covering 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, LPG[2] and TSIB[3].
The LPG simulates the behavior of every single resident of a household and generates corresponding agent-based 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 TSIB in order to calculate the total heat demand. Here, the heat output of single residents

[2] Load Profile Generator (LPG), available at: https://github.com/FZJ-IEK3-VSA/LoadProfileGenerator
[3] Time Series Initialization for Buildings (TSIB), available at: https://github.com/FZJ-IEK3-VSA/tsib

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is calculated based on their activity profiles. Furthermore, the heating load is determined via TSIB by means of a simplified 5R1C thermal building model [35]. This model 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 temperature, the load profiles for heating are calculated for the reference years 2020 and 2050 [36]. For each of the ten buildings, the building envelopes are considered without renovation, as well as with two levels thereof, with each of the three having different supply temperatures. If no renovation is considered, the original building envelope from the TABULA database is used. With respect to the renovation levels, level 1 reduces specific heating demand by 74% and level 2 by 78% compared to an un-renovated building for the oldest SFH selected. The renovation costs, specific heat demand levels, and heat supply temperature for each building and all three renovation levels, are shown in Table 6.
As these levels of renovation were each considered for the ten selected buildings and two reference years, 60 heating profiles were generated. Figure 2 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.

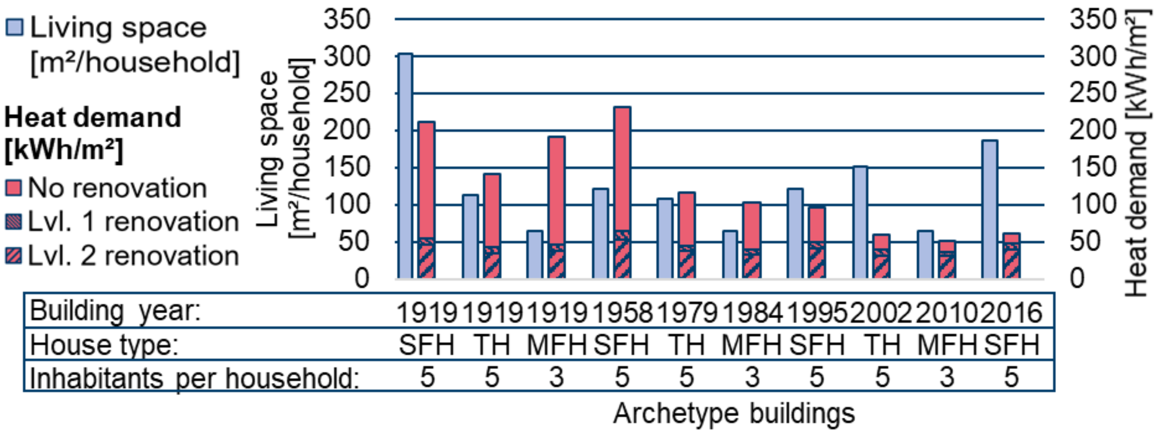

Figure 3. Building selection from the German building stock with living space and heat demand for three different levels of renovation.

In addition to the demand profiles, there is also a need for 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. [37].

2.2 Modeling of building energy systems

The cost-optimal energy system 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.

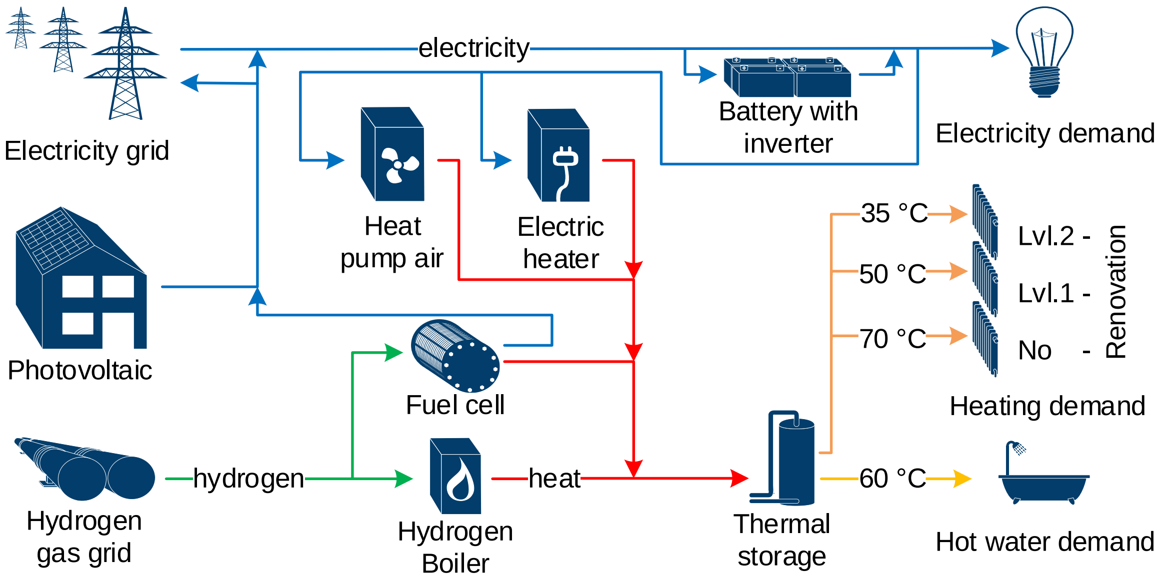

Figure 4. Technology pool and interconnection of possible building energy systems.

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 customer, 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 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 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 heat pump tariff 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 % in 2020 and 26 % in 2050 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 2020 and 0.08 €/kWh$_{el}$ in 2050.
Hydrogen from the public gas grid can be converted into heat by means of a hydrogen boiler, or into heat and electricity using a fuel cell. The fuel cell is modeled as two different sub-components, depending on the respective technology. The SOFC generates 600 °C of heat [38], which is then reduced to 70 °C to be used in the system and is able to operate by modulating 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. Both fuel cells are modeled with an operational subsidy for 2020, corresponding to the German Federal Office of Economics and Export Control (bafa). This subsidy is paid for 6,000 full load hours per year over 10 years, which is the lifetime of the fuel cells. It includes 0.04 €/kWh$_{el}$ for self-consumed electricity and 0.08 €/kWh$_{el}$ for electricity sold into the grid [39]. On top of the funding for grid sales, a CHP-Index of 0.05 €/kWh$_{el}$ is paid. With respect to storage components, the technology pool contains a lithium-ion battery and a thermal storage system that is set to a capacity of 300 liters. In order to represent a single thermal storage with multiple levels of temperature, the thermal storage is modeled as five sub-components sharing the storage volume with temperatures of 35, 50, 60, 70, and 90 °C each. From 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 these levels, which are supplemented by the 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 in Table 2 for 2050, are defined for the system components, both for purchasable energy carriers, salable electricity, and the funding of the fuel cells. 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, with 0.2 €/kWh$_{th}$ [40]. For the year 2050, we assume that the price of green hydrogen is halved. 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	3500	€	8800	€/kW$_{el}$	300	€	20	€/kW$_{el}$	10	years	Own as.
SOC fuel cell	4300	€	5500	€/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	[41]

Table 1. Economic parameters for 2020. Parameters from internal sources of IEK-3 are marked as own assumptions (own as.). Costs for balance of plant, energy management and safety controlling systems are included in the component costs. We assume an annual economic interest rate for the 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	[42, p.]
PEM fuel cell	4000	€	1500	€/kW$_{el}$	120	€	45	€/kW$_{el}$	15	years	[43]
SOC fuel cell	4000	€	1500	€/kW$_{el}$	120	€	45	€/kW$_{el}$	15	years	[43]
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	[41]

Table 2. Economic parameters for 2050. Parameters from internal sources of IEK-3 are marked as own assumptions (own as.). Costs for balance of plant, energy management and safety controlling systems are included in the component costs. We assume an annual economic interest rate for the 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	
SOC 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 [45]	
	COP_{max}	5.0			
Heat pump at 50 °C	COP_{min}	2.7		Own calculations according to [45]	
	COP_{max}	4.6			
Heat pump at 70 °C	COP_{min}	2.2		Own calculations according to [45]	
	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 %	[41]	[46]
	$\eta_{discharge}$	95 %	95 %	[41]	[46]
	Self-discharge	0.01 %/h	0.01 %/h	Own assumptions	[46]
Thermal storage	η_{charge}	99 %	99 %	[45]	
	$\eta_{discharge}$	99 %	99 %	[45]	
	Self-discharge	0.1 %/h	0.1 %/h	Own assumptions	

Table 3. Technical parameters for 2020 and 2050.

2.3 Optimization with FINE

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)[4] [47]. The optimization goal is to minimize the total annualized costs (TACs) of each building's energy system for the target years of 2020 and 2050.

For this purpose, this paper performs two studies. First the optimal TACs 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 the use in heat pumps. With respect to hydrogen, a price of 0.2€/kWh$_{H2}$, referring to the lower heating value, is assumed for 2020, and 0.1 €/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 thresholds of the hydrogen price at which it would become economically viable to use. In addition, this approach can be

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

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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 taken into account.

	Commodity	Price		Source
Subsidy-, purchasing and sales prices for both approaches	Fuel cell subsidy for self-consumed electricity (only for 2020 and for 6,000 vlh)	0.04	€/kWh$_{el}$	[39]
	Fuel cell subsidy for electricity sold into the grid (only for 2020 and for 6,000 vlh)	0.08	€/kWh$_{el}$	[39]
	Photovoltaic subsidy for electricity sold into the grid (only for 2020)	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
Approach 1: Fix commodity prices	**Commodity**	**Price**		**Source**
	Electricity purchasing (2020 & 2050)	0.308	€/kWh$_{el}$	Own assumptions
	Hydrogen purchasing (2020)	0.2	€/kWh$_{th}$	Own assumptions
	Hydrogen purchasing (2050)	0.1	€/kWh$_{th}$	
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

In this study we investigate the role of hydrogen in German buildings. First, we examined the selected buildings and their cost-optimal energy systems for fixed prices for the purchasing of electricity and hydrogen. Techno-economic assumptions were made for the target years of 2020 and 2050, as described in chapter 2.2 and 2.3. In a second analysis, we analyzed the sensitivity of the electricity and hydrogen prices with the aim of identifying the quantitative use of energy sources and the technology selection made. In order to gain deeper insight into the impact of a declining hydrogen price on technology selection and renovation efforts, the development of energy systems is also viewed from this perspective. Figure 5 shows the structure of this chapter.

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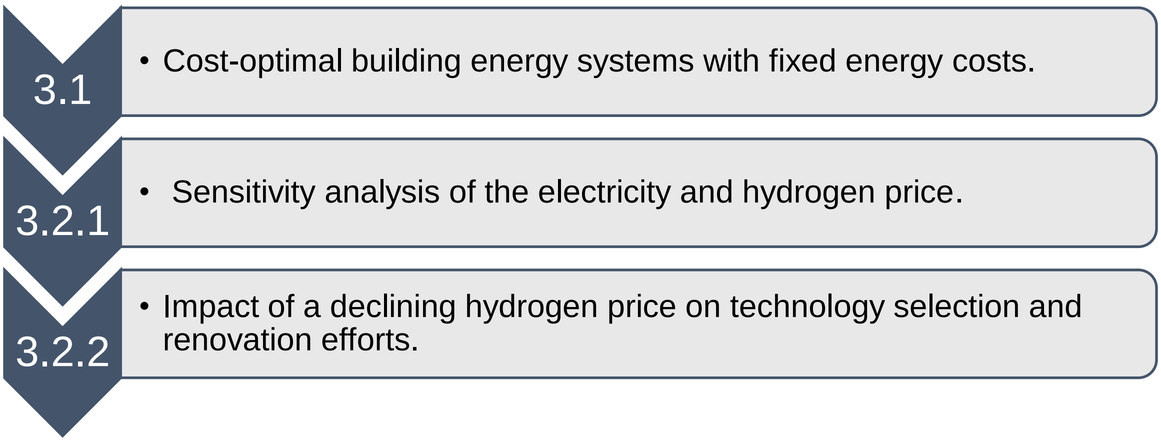

Figure 5. Flowchart of the proceedings in the results and discussion chapter.

3.1 Optimal TAC with fixed electricity and hydrogen prices

The first analysis in this study examined the selected buildings and their cost-optimal energy systems for fixed prices for the purchasing of electricity and hydrogen. Figure 6 illustrates the TAC structure for these of the cost-optimal energy systems regarding the examined SFHs and THs for both target years, taking into account the renovation levels. Figure 7 illustrates the same for MFHs. For the target year 2020, 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 [14]. 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 TAC structure for lowering the 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 [48].

The results for the target year of 2050 significantly differ. For SFHs and THs, hydrogen boilers are used everywhere except in the oldest buildings due to the comparatively low assumed price of hydrogen of 0.10 €/kWh_{H2} for the target year of 2050, with a constant high electricity price of 0.31 €/kWh_{el}, respectively 70 % of it (0.22 €/kWh_{el}) as reduced price for heat pumps. In the oldest building, a heat pump is used in combination with a PEM fuel cell system that produces electricity that the heat pump uses to cover the peaks (even if renovated) of the high heat demand. The cost-optimal energy systems for MFHs use fuel cells for the target year 2050. Fuel cells are used as CHP systems to produce heat and electricity due to the low price of hydrogen and because of the proportionally high electricity demand and comparatively low rooftop PV potential of MFHs with regard to their heat demand. Less renovation was chosen for the target year of 2050 in comparison to the results of 2020. For 2050, only SFHs built around 1960 and earlier are renovated for the cost-optimal coverage of their heating demand, and so the period before a renovation becomes economical and extends from 30 to 90 years. The diminished economic benefits of renovation measures are due to the cheaper hydrogen price assumed for 2050, which reduces the need for lower heating demand.

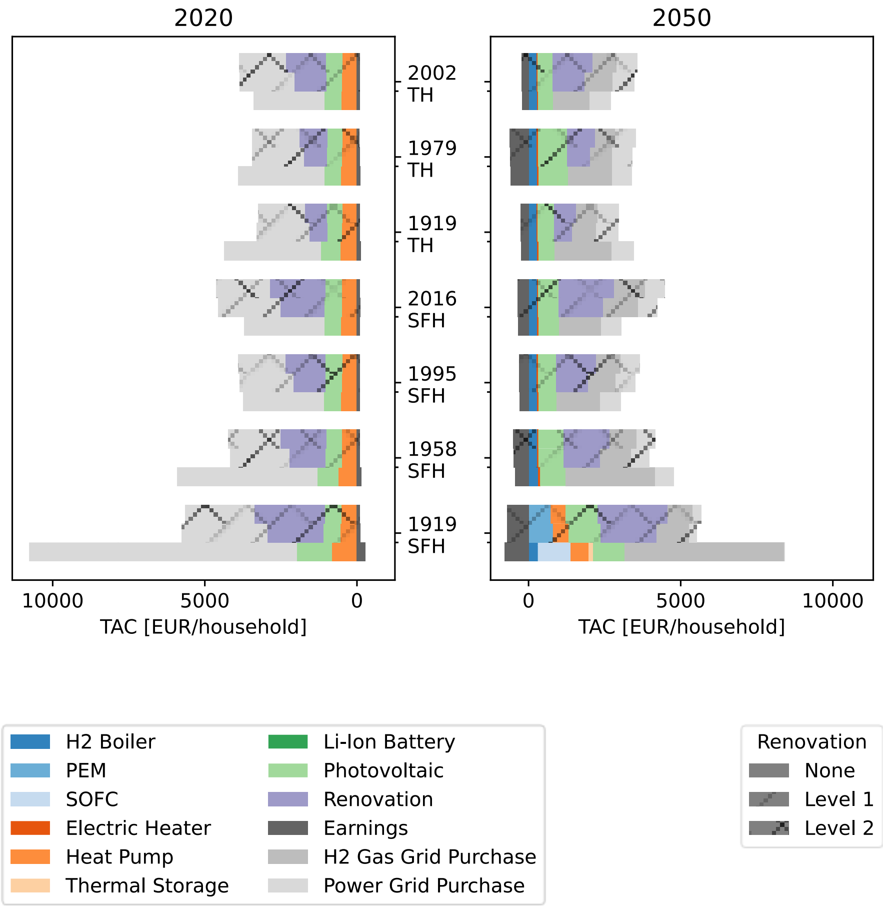

Figure 6. Optimal TAC structure for the examined SFHs and THs sorted by building year and renovation level.

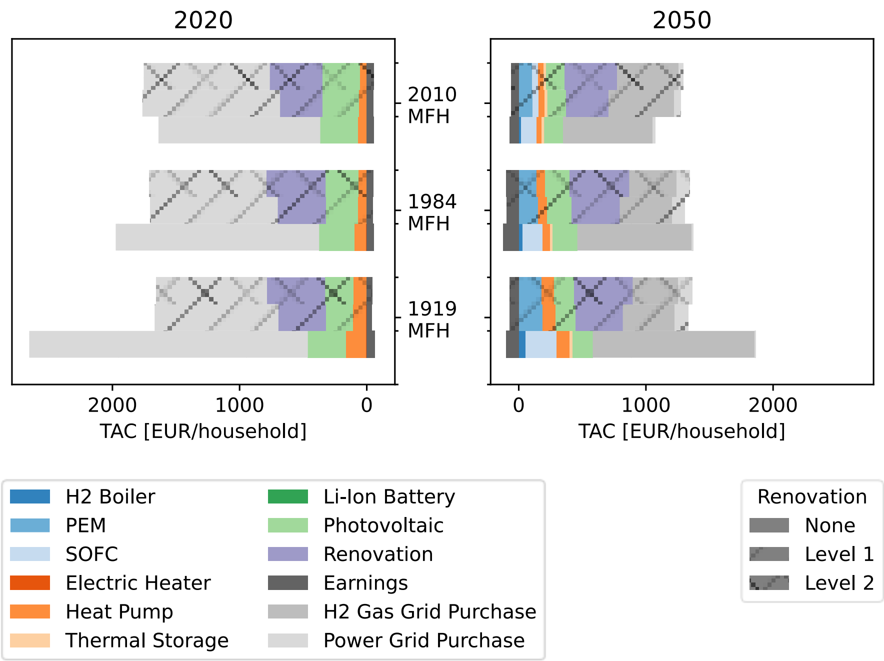

Figure 7. Optimal TAC structure for the examined MFH sorted by building year and level of renovation.

3.2 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 over all of the buildings analyzed. In order to gain deeper 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 Analysis of hydrogen usage and technology selection by building type

The results shown in Figure 8 indicate the threshold values for the economical use of hydrogen in the selected SFHs and THs with building years between 1995 and 2016. The colors indicate how strong the share of hydrogen in the heat supply of the considered buildings is. For values above one, hydrogen is also used for electricity generation in addition to heat 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 both at 0.13 €/kWh_{H2}. The influence of the different assumed hydrogen prices for 2020 (0.2 €/kWh_{H2}) and 2050 (0.1 €kWh_{H2}) can also be seen in Figure 8. There is virtually no usage of hydrogen in 2020 due to the economic advantage of electricity in its assumed price range. For 2050, a high use of hydrogen is observed, such that 100 % of heat demand is covered by hydrogen. From these results, an electricity to hydrogen price ratio can be derived, above which the use of hydrogen is economically viable. This ratio ranges between 2.14 and 2.71 for 2020 and 2050 for the examined SFH.

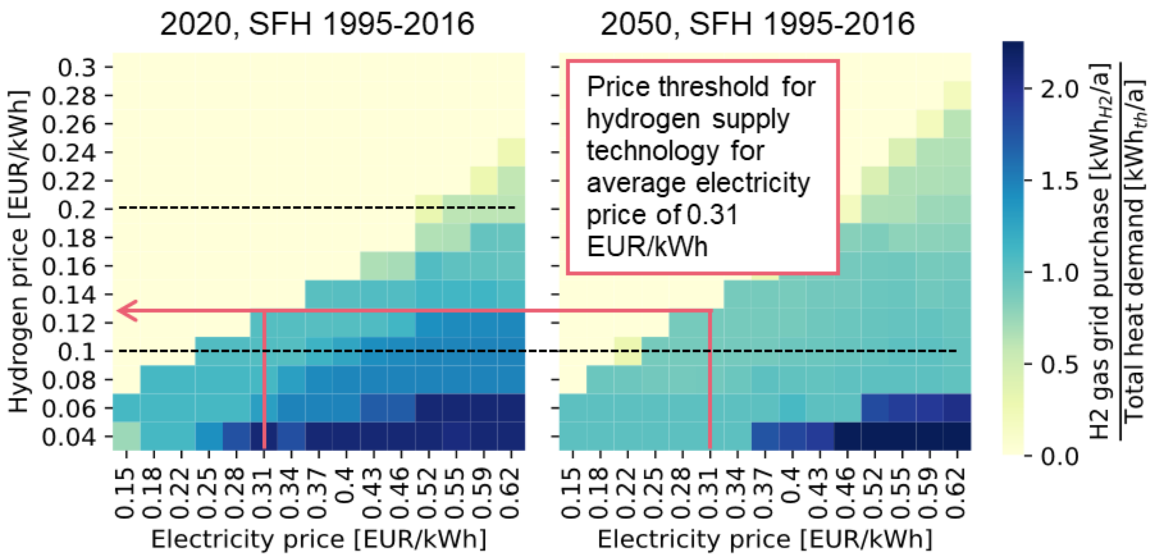

Figure 8. Price sensitivity for SFHs and THs with building years between 1995 and 2016 with cost-optimal technology configurations and renovation choices. The colors indicate the factor of hydrogen purchasing to total heat demand (space heating and warm water) in kWh per year.

Figure 9 shows the afore mentioned results for SFHs with building years from 1919 to 1979. Here as well, the price thresholds for hydrogen supply technology for the assumed electricity price of 0.31 €/kWh$_{el}$ are the same but lower as for the newer buildings at 0.11 €/kWh$_{H2}$, for 2020 and 2050. The derived electricity to hydrogen price ratio ranges between 2.14 and 2.82 for 2020 and 2050.

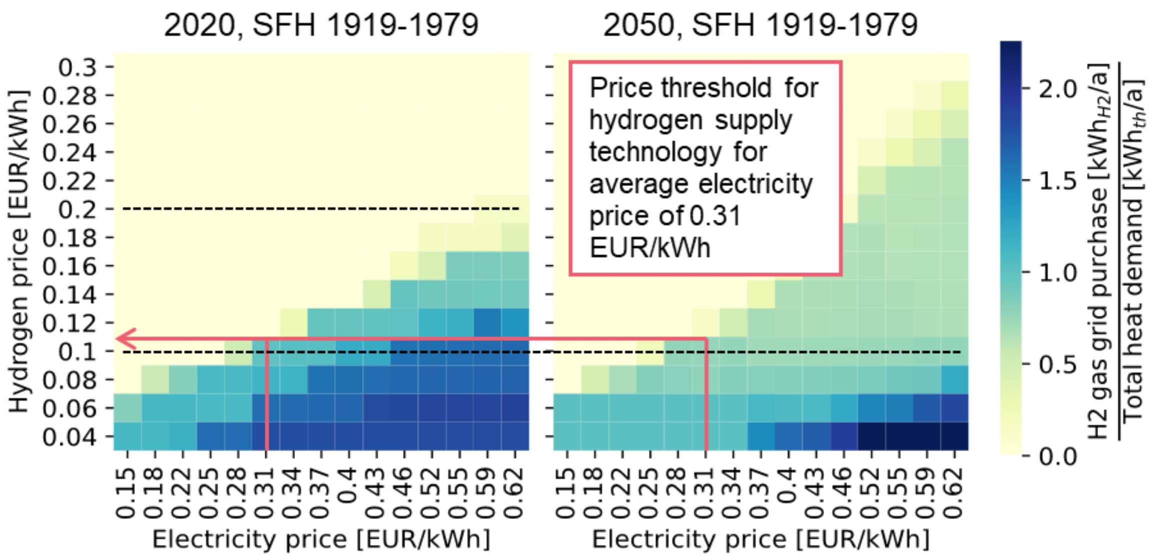

Figure 9. Price sensitivity for SFHs and THs with building years between 1919 and 1979 with cost-optimal technology configurations and renovation choices. The colors indicate the factor of hydrogen purchasing to total heat demand (space heating and warm water) in kWh per year.

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 slightly between 2020 and 2050, from 0.14 €/kWh$_{H2}$ up to 0.15 €/kWh$_{H2}$ for the MFH built 1919 and from 0.16 €/kWh$_{H2}$ up to 0.17 €/kWh$_{H2}$ for the MFHs built 1984 and 2010. The two MFHs from 1984 and 2010 are shown in Figure 10. 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 there to cogenerate heat and power. These fuel cell CHP systems are assumed to be less expensive in 2050 than 2020, so, in contrast do SFH, where hydrogen boilers are used, the use of hydrogen becomes economically more viable in 2050 than in 2020. The electricity to hydrogen price ratios derived for 2020 range from 1.84 to 2.14 and for 2050 it is between 1.67 and 1.82.

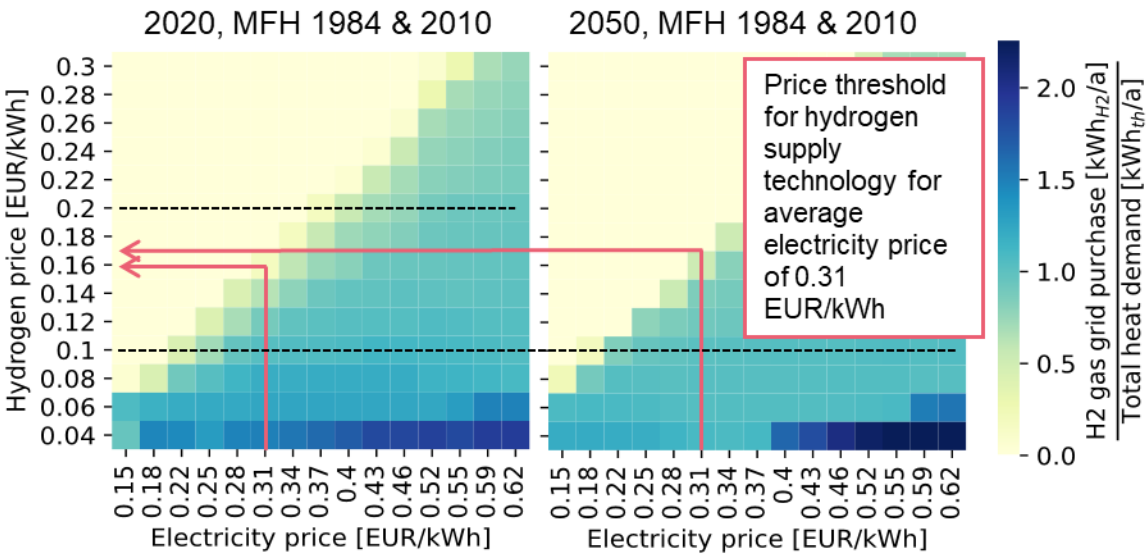

Figure 10. Price sensitivity for MFHs built 1984 and 2010 with cost-optimal technology configurations and renovation choices. The colors indicate the factor of hydrogen purchasing to total heat demand (space heating and warm water) in kWh per year.

The cost-optimal technology selection for SFHs and THs depending on the price of hydrogen and electricity can be seen in Figure 11. These results support the analysis in chapter 3.1, which concerns the use of hydrogen boilers in 2020. For the target year of 2050, the technology selection is more complex, featuring a combination of different technologies. For a hydrogen price below 0.08 €/kWh$_{H2}$ and a low to medium-high electricity price, hydrogen boilers are favored. With an increasing hydrogen price, these are combined with electric heaters. An even higher electricity price with a simultaneously rising hydrogen price in combination with heat pumps and fuel cells represents the cost-optimal technology selection. Fuel cells alone are only used when a high electricity price meets a low hydrogen price of less than 0.07 €/kWh$_{H2}$.

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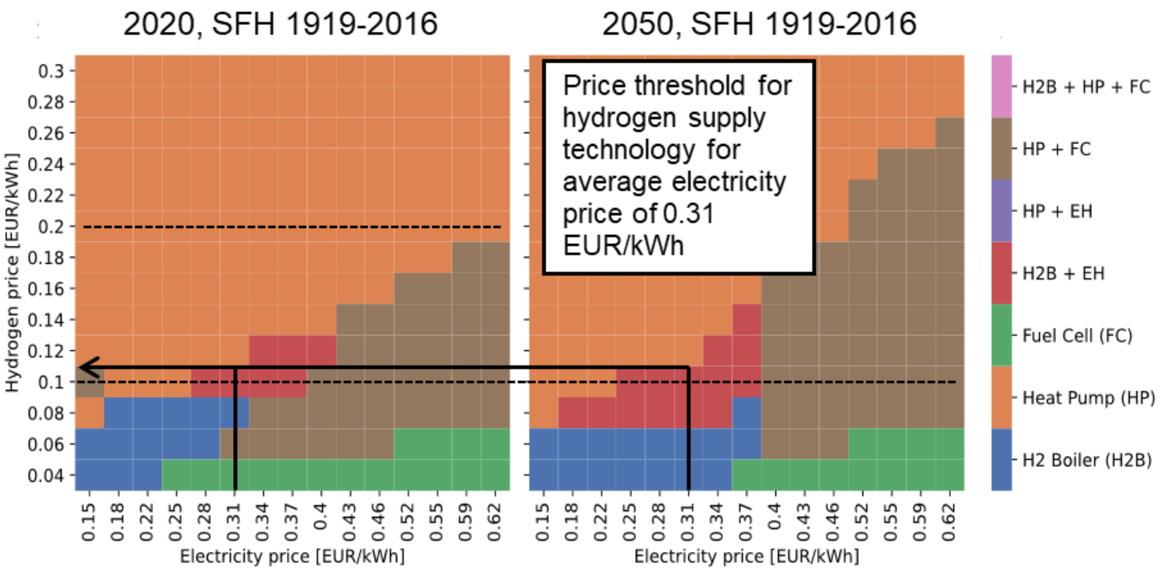

Figure 11. Price sensitivity for SFHs and THs with cost-optimal technology configurations and renovation choices. The colors indicate the predominant supply technology for heating over the building type group.

Technology selections for MFHs, depending on hydrogen and electricity prices, are displayed in Figure 12. For the target year of 2020, the already in the previous chapter identified use of heat pumps can be observed, in combination with electric heaters. If the ratio of hydrogen and electricity prices decreases in favor of hydrogen, the combination of heat pumps with fuel cells is used in cost-optimal systems. For 2050, fuel cell systems are used in combination with heat pumps. If the hydrogen price is below 0.09 €/kWh$_{H2}$, the aforementioned combination is extended by 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 electricity price is in the extreme high end of the assumed range above 0.57 €/kWh$_{el}$ and the hydrogen price is extremely low, below 0.06 €/kWh$_{H2}$, which is a fairly unrealistic constellation.

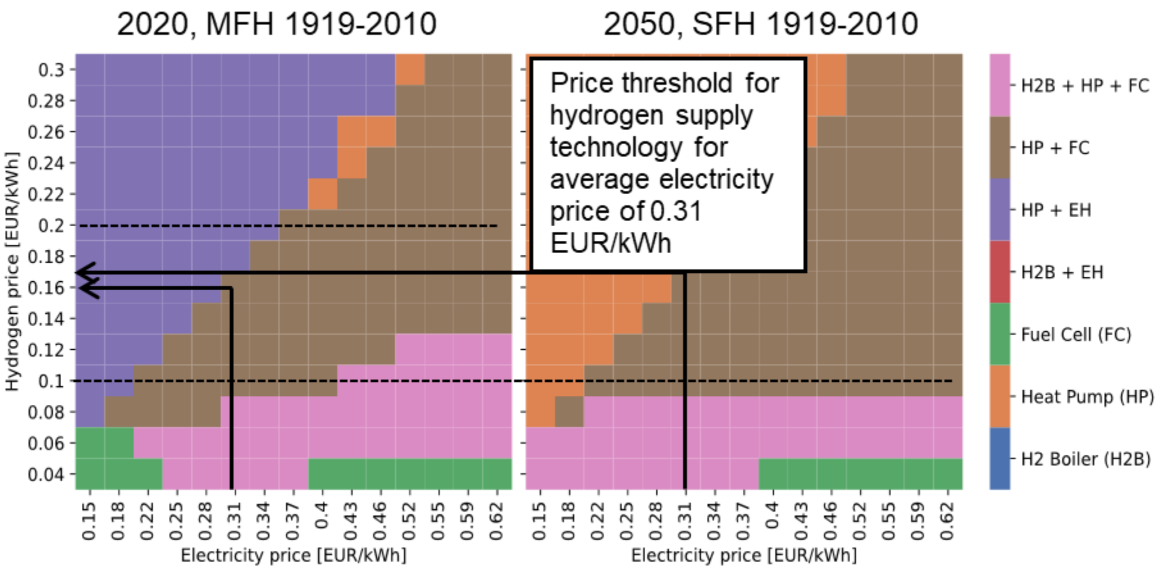

Figure 12. Price sensitivity for MFHs with cost-optimal technology configurations and renovation choices. The colors indicate the predominant supply technology for heating over the building type group.

3.2.2 Analysis of the hydrogen-sensitive system structure for two selected buildings

A deeper 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 considered and include the technology selection, the 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, and all other diagrams can be found in the appendix.

First, a TH for single families optimized for the year 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 16,500 kWh$_{th}$. Up to a hydrogen price of 0.07 €/kWh$_{H2}$, only a hydrogen boiler is used for heat generation purposes. For a higher hydrogen price of up to 0.09 €/kWh$_{H2}$, a photovoltaic operated electric heater supports the hydrogen boiler, which reduces its operation. Beyond this price, up to nearly 0.11 €/kWh$_{H2}$, the operation of the hydrogen boiler is significantly reduced by half, and a renovation choice is made to reduce the heat demand. Above 0.11 €/kWh$_{H2}$, hydrogen is no longer used in the building's energy system, and heat pumps are used instead.

On the basis of 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 0.09 €/kWh$_{H2}$, heating is primarily performed with hydrogen, in part with minor support from an electric heater. Beyond this threshold, the building is renovated for a lower heating demand. At 0.11 €/kWh$_{H2}$, there is a second threshold price for hydrogen at which it is no longer utilized, but a heat pump is used instead. For renovation measures, the observed building indicates that a not unrealistic low hydrogen price of 0.09–0.10 €/kWh$_{H2}$ leads to the fact that no renovation must be carried out for a cost-optimal building heat supply.

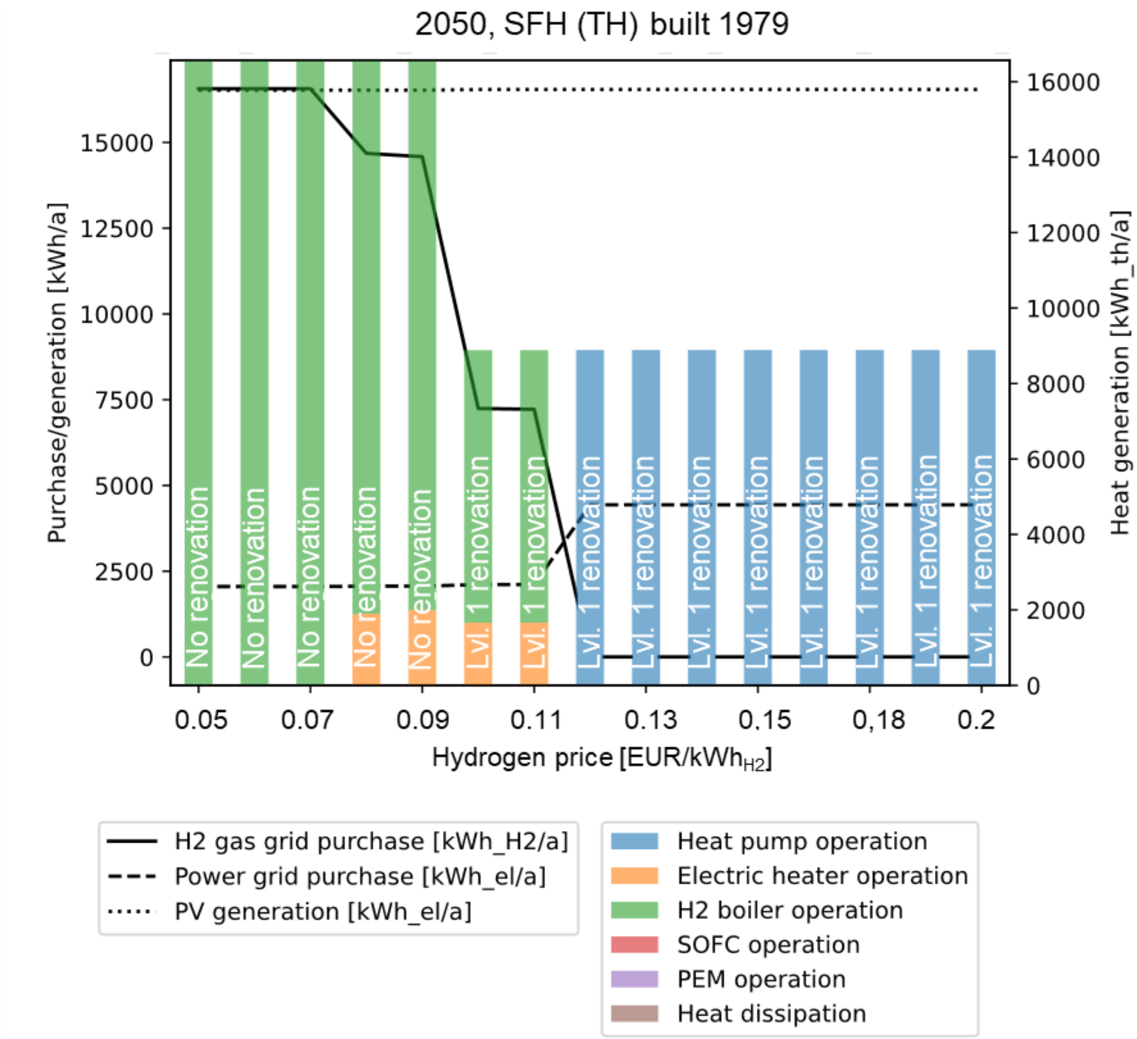

Figure 13. Price sensitivity for a TH (built in 1979, 108 m² living area) with its cost-optimal technology configuration and renovation choices for 2050.

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, and the following insight can be drawn from its data. 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. At a price of 0.1 €/kWh$_{H2}$, a significant change in the system structure can be observed. In order to reduce the heat demand, the building is renovated, and heat is generated through a combination for a heat pump and PEM fuel cell. With this change in the system's structure, the purchasing of hydrogen is halved. The PEM is chosen because of its higher operational flexibility. This is due to its ability to modulate freely, whereas the SOFC operates with at least 0.33 % of its capacity. With an increasing hydrogen price of up to 0.163 €/kWh$_{H2}$, the purchase of hydrogen decreases, as more electricity is drawn from the grid. Above this price, no more hydrogen is purchased, and the building is renovated to the best possible level. The reduced 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, two individual threshold values for the hydrogen price can be derived

for the analyzed MFH built in 1984. At a price of 0.01 €/kWh$_{H2}$, a change from high to low hydrogen use takes place, which is compensated by renovation measures. The next threshold value is 0.163 €/kWh$_{H2}$, above which no hydrogen is used, and renovation measures are intensified.

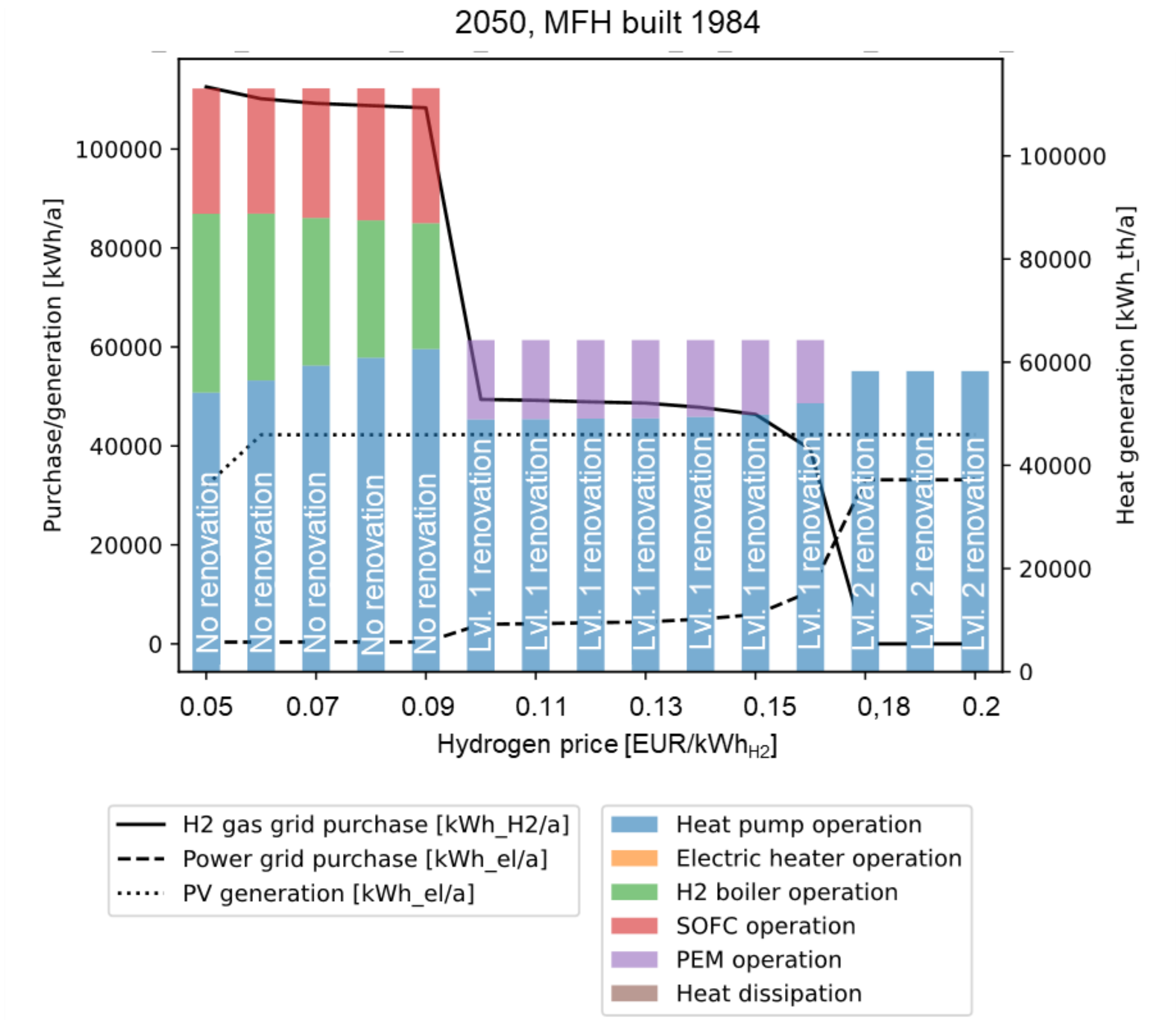

Figure 14. Price sensitivity for an MFH (built in 1984, with 778 m² total living area for 12 households) with its cost-optimal technology configuration and renovation choices for 2050.

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 our results, we aim to derive initial basic statements regarding the role of hydrogen for typical buildings from the German building stock. For the examined SFHs, including terraced houses, a hydrogen price of up to 0.11 €/kWh$_{H2}$ leads to the use of hydrogen in building energy systems for 2020 and 2050. The corresponding threshold price for the investigated MFHs, except for the oldest one, is 0.16 €/kWh$_{H2}$ for 2020 and 0.17 €/kWh$_{H2}$ for 2050, mainly triggered by fuel cell operation. We identify a hydrogen price of up to 0.11 €/kWh$_{H2}$ in order to heat all the buildings studied with hydrogen in 2050 in an economically viable for the assumed energy carrier prices.

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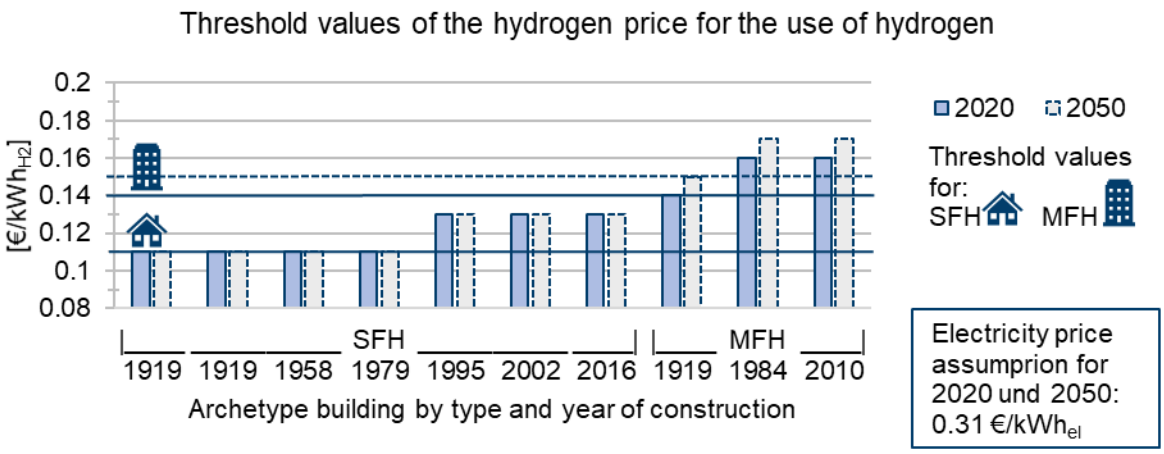

Figure 15. Threshold prices for the use of hydrogen, based on a sensitivity analysis of SFHs and MFHs.

For 2020, no economically viable use of hydrogen in German residential buildings can be derived from the results, as the costs of green hydrogen in German residential buildings were determined to be 0.2 to 0.31 €/kWh$_{H2}$. This does not match with any of the identified threshold values for 2020. For 2050, the costs determined from [31] range between 0.17 and 0.24 €/kWh$_{H2}$. At this cost, hydrogen could be used in an economically viable only in the MFHs from 1984 and 2010. Though, according to [26], production costs of green hydrogen could decrease significantly more, which would result in a hydrogen price for residential buildings of 0.12 €/kWh$_{H2}$. For this price, all buildings examined, except the four oldest SFHs, could use hydrogen in an economically viable way for their energy systems. As for those four older SFHs, renovation and thereby reducing the heat demand and supply temperature in combination with heat pumps which draw electricity from a PV system is economically more viable, than the use of hydrogen. For those four SFHs, where no economically viable use of hydrogen could be investigated for 2050, price signals such as subsidies from policy could help make hydrogen usable on a large scale.
The threshold values for 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 efficiency or the costs of hydrogen boilers. In contrast, threshold values differ for both target years if MFHs are considered. This is because fuel cell CHPs are used in combination with hydrogen boilers and heat pumps. In MFHs, there is proportionally higher electricity demand compared to SFHs, and so the cogeneration of heat and power makes fuel cell CHPs profitable, even more so with the lower hydrogen price assumed for 2050. This analysis reveals that the hydrogen price is not prohibitive for the use of hydrogen in buildings. Much more important is the question of how to distribute, at least initially, small amounts of hydrogen, which is a political decision.

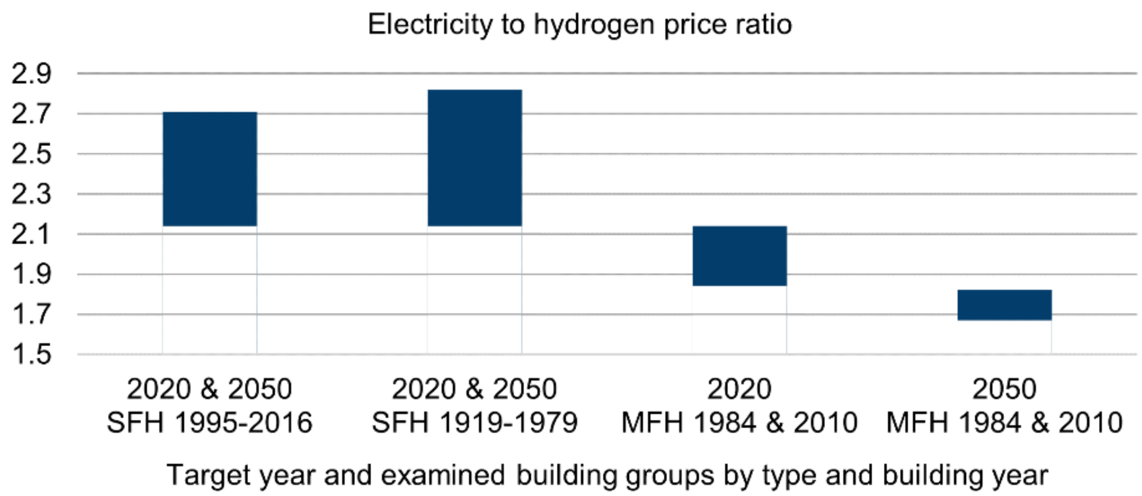

Figure 16. Electricity to hydrogen price ratio for the examined building groups.

The electricity to hydrogen price ratio, as presented in Figure 16, shows the relation of the electricity to the hydrogen price, above which the use of hydrogen is economically viable in each building group and target year. These ratios range from 1.67 to 2.82, 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 ratio of 2.5 can be determined for SFH and 1.8 for MFH, which is favored by the use of CHP. The lower ratio indicates that hydrogen could be more expensive, compared to the electricity price, than with a higher ratio, for an economically viable use of hydrogen. Our ratios determined are pretty low, compared to the corresponding ratio for natural gas in Germany, which is at 4.2 due to the high electricity and low natural gas price.

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 measure shows that buildings built in 1990 and earlier are renovated based on our assumptions for 2020. With our assumptions for the target year of 2050, buildings built around 1960 and earlier are renovated for the cost-optimal coverage of their heat demand, due to the lesser hydrogen price, which makes it possible to achieve a large heating capacity at a relatively low cost.

In the building sector as it currently stands, heat pumps are a well-functioning alternative for hydrogen. They are almost six times more efficient than heating with green hydrogen fueled boilers, which reduces necessary primary energy generation significantly [33]. Despite these clear disadvantages in terms of efficiency, our analyses show that a comparatively low hydrogen price can compensate for the advantages of heat pumps. A key argument for the use of hydrogen in general is its ability to provide flexibility in the process of decarbonizing multiple sectors [8]. In general, hydrogen is seen as a major chance for 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 [20]. However, it can be observed that due to an increased emergence 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 electrolyzers are operated from surplus electricity from wind power, as well as in the Ruhr area, where industrial demand is particularly high. In addition, rededication of existing gas grids prevents their complex and cost-intensive dismantling. Finally, electrification of some types of houses is not possible in some cases due to space restrictions or monument protection. Here, the supply of hydrogen can represent an alternative to the district heating network. The technology selection can be controlled by price signals. If heat pumps in buildings are politically desired, the price of electricity must be determined accordingly and fall significantly. Under the current regulatory framework, hydrogen can play a major role for supplying the heat demand of the buildings if the prices develop as predicted. Nevertheless, in order to favor heat pumps as supply option, as the macro-analysis of other researchers request, the price of electricity must be determined accordingly and fall significantly.

5 Conclusions

This bottom-up study investigated the role of hydrogen for the climate-neutral energy supply, taking into account renovation measures of 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. We performed sensitivity analyses which resulted in threshold values of the hydrogen price for its use in residential buildings. These results show that under the current regulatory framework hydrogen can play a significant role in German residential buildings in the future and the price of hydrogen does not appear to be a showstopper for its use in this sector. We identified a hydrogen price of up to 0.11 €/kWh$_{H2}$ in order to heat all the buildings studied in parts with hydrogen in 2050 in an economically viable way. Also, electricity to hydrogen price ratios for the economically viable use of hydrogen in the examined buildings was determined. Our ratios range from 1.67 to 2.82 and we can make the general statement that above these values an economically reasonable use of hydrogen in buildings can be possible, not only in Germany. For the individual building groups for the year 2050, a ratio of 2.5 can be determined for SFH and 1.8 for MFH, which is favored by the use of CHP.
A well-functioning and more efficient alternative for hydrogen in the building sector are heat pumps, often in combination with energy refurbishment. Nevertheless, in order to favor heat pumps as supply option, as the macro-analysis of other researchers request, the price of electricity must be determined accordingly and fall significantly and refurbishment rates must be defined, and their realization supported. The technology choice, whether hydrogen- or electricity-based systems, can be driven by price signals, which in turn requires a policy decision. If there is an existing gas grid that can be used for hydrogen transportation and distribution, it would be reasonable to assume that this could be possible at low costs.
In the next step, further research is needed on the topic of future costs of green hydrogen for the use in residential buildings, considering costs for the hydrogen distribution grids for the connection of buildings. Also, more detailed investigations could be useful with regard to the use of hybrid gas boiler/heat pump appliances, as this combination is being heavily promoted at the time of writing. 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.

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 **[34]**.

Building ID from TABULA **[34]**	No renovation (T^{sup}=70 °C)	Level 1 renovation (T^{sup}=50 °C)		Level 2 renovation (T^{Sup}=35 °C)			
	Spec. heat. [kWh_{th}/m2]	Cost [EUR]	Spec. heat. [kWh_{th}/m^2]	Cost [€]	Spec. heat. [kWh_{th}/m^2]	Hot Water [kWh_{th}/pers.]	Elec. Appl. [kWh_{el}/pers.]
DE.N.SFH.03	210.65	47,344.86	54.94	59,558.95	45.92	811.67	884.88
DE.N.TH.03	141.76	15,300.11	42.37	18,767.55	34.94	811.67	884.88
DE.N.MFH.03	191.41	57,186.22	45.86	71,165.86	37.10	794.85	767.12
DE.N.SFH.05	231.13	30,490.17	64.73	38,730.19	52.53	811.67	884.88
DE.N.TH.07	115.81	19,350.17	44.68	23,841.14	37.18	811.67	884.88
DE.N.MFH.08	102.45	116,417.36	40.33	144,011.54	32.61	913.92	875.97
DE.N.SFH.09	96.20	27,164.83	49.86	33,954.40	40.48	811.67	884.88
DE.N.TH.10	59.68	27,105.69	39.39	33,679.42	31.78	811.67	884.88
DE.N.MFH.11	51.84	171,321.32	36.55	211,933.88	30.62	926.82	1049.23
DE.N.SFH.12	61.22	37,436.64	47.52	46,840.82	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.

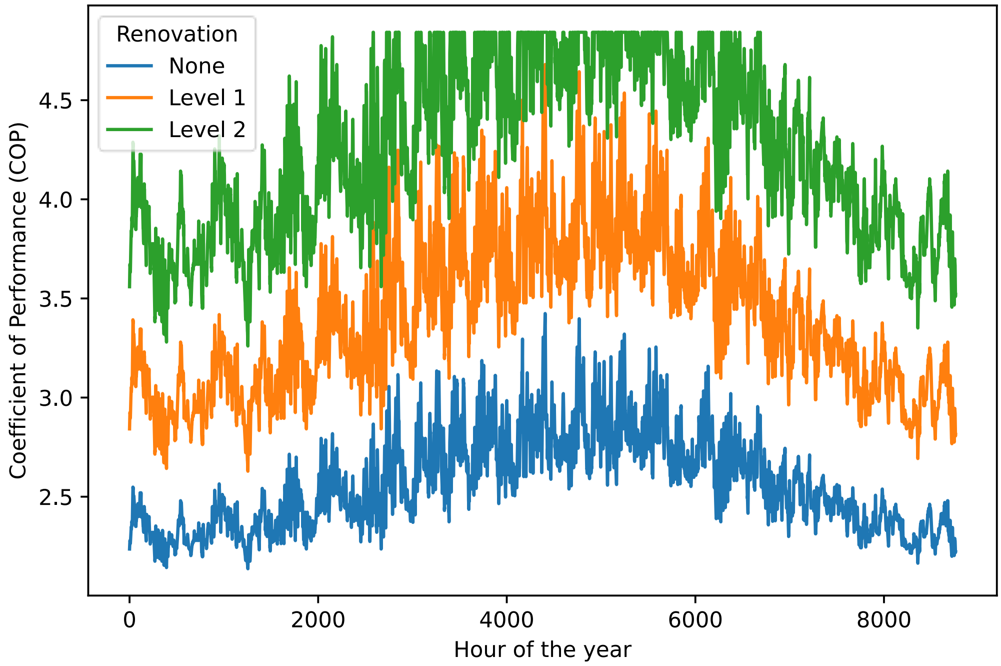

Figure 17. COP time-series for each heat pump sub-component, calculated according to [45].

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

[7] 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

[8] 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).
[9] 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.
[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] 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
[12] 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
[13] 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.
[14] 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.
[15] P. Gerbert *et al.*, "Klimapfade für Deutschland," Bundesverband der Deutschen Industrie e.V. (BDI), 2018.
[16] 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
[17] 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
[18] 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
[19] 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.
[20] 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.
[21] 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.
[22] Bosch Thermotechnology Ltd., "Hydrogen Boiler | Worcester Bosch." https://www.worcester-bosch.co.uk/hydrogen (accessed Jul. 23, 2021).
[23] 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.
[24] 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).
[25] 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.
[26] IRENA, "Hydrogen: A renewable energy perspective," International Renewable Energy Agency, Abu Dhabi, 2019.
[27] 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).
[28] Bundesnetzagentur, "Netzentgelt (Strom und Gas)," 2021. https://www.bundesnetzagentur.de/SharedDocs/A_Z/N/Netzentgelt.html (accessed Aug. 23, 2021).
[29] 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
[30] BMWI, "Staatlich veranlasste Bestandteile des Gaspreises," 2021. https://www.bmwi.de/Redaktion/DE/Artikel/Energie/gaspreise-bestandteile-staatlich.html (accessed Aug. 25, 2021).
[31] 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
[32] EHPA Stats, "Energy prices: electricity vs. gas," 2020. http://www.stats.ehpa.org/hp_sales/story_prices/ (accessed Aug. 31, 2021).
[33] 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
[34] Institut für Wohnen und Umwelt, "EPISCOPE and TABULA Website." https://episcope.eu/iee-project/ (accessed Jun. 24, 2021).
[35] 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.
[36] DWD, "Testreferenzjahre (TRY) 2011." https://www.dwd.de/DE/leistungen/testreferenzjahre/testreferenzjahre.html (accessed Jun. 25, 2021).
[37] 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.
[38] 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.
[39] Bundesamt für Wirtschaft und Ausfuhrkontrolle, "BAFA - KWK-Anlagen bis 50 kWel." https://www.bafa.de/DE/Energie/Energieeffizienz/Kraft_Waerme_Kopplung/Stromverguetung/Stromverguetung_bis_50_KW/stromverguetung_bis_50_kw_node.html (accessed Jul. 01, 2021).
[40] 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
[41] 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

[42] 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.
[43] 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.
[44] 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).
[45] 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.
[46] D. Sauer *et al.*, *Energiespeicher - Technologiesteckbrief zur Analyse „Flexibilitätskonzepte für die Stromversorgung 2050“*. 2015. doi: 10.13140/RG.2.1.1478.4409.
[47] 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.
[48] 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).