Decarbonising the residential heating sector: a techno-economic assessment of selected technologies

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Abstract

To decarbonise the energy system, higher shares of renewable energy sources are needed, but increase flexibility requirements due to their volatility. The electrification of residential heat incurs large electricity demands and could further increase flexibility requirements if not scheduled properly. However, optimised operation of these coupled sectors could also yield flexibility. For instance, temporarily increasing room temperature with heat pumps and seasonal hydrogen(H_2) storage entail flexibility potentials. Here, waste heat of fuel cells coincides with hydrogen usage for power supply during winter. However, these means of heat provision require costly building refurbishments. Alternatively, hydrogen combustion, providing high-temperature heat with already existing infrastructure, could be cost-efficient for the transition phase towards a renovated building stock. The described means for heat provision are analysed with a building model implemented with endogenous heat demand within an energy systems modelling framework. Emission reductions are then applied and sensitivity analyses for varying indoor temperatures and H_2 prices are performed. The results show that using solar PV and heat pumps in conjunction with electrolysers and fuel cells is more cost-efficient than refurbishments. Hydrogen combustion is only used when hydrogen prices fall below gas prices, or a very high lower temperature limit is applied.

Keywords: Residential Heat, Power-to-Heat, Sector Coupling, Seasonal

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energy storage, Hydrogen

1. Introduction

To limit the impacts of global warming, the energy system as a whole, including all energy demanding sectors, needs to be decarbonised rapidly. This implies vast changes, especially in the sectors of industry, transportation and buildings, since these have historically demanded the largest shares of energy and are thus in large part responsible for most of the greenhouse gas emissions. For instance, in 2018, roughly 26% (644 TWh) of the total German energy demand was required in the residential building sector, 80% of which were used for space heating and the provision of domestic hot water, which are fuelled mainly by fossil fuels [1]. In order to comply with the newly passed legislation to reduce the emissions of the building sector by 40 % from current levels by 2030 [2], measures to reduce energy demand and to increase energy efficiency are mandatory. Improving the building shell with refurbishments might enable the greatest energy savings, but refurbishments have been rolled out insufficiently to put Germany on a trajectory to reach its climate goals in this sector [3]. In addition to building refurbishments, energy efficiency improvements and a shift towards renewable heat provision are required [4]. This is adding to the already existing requirement for higher shares of variable renewable energy (VRE) sources to decarbonise the energy system, which increases the demand for flexibility, so as to be able to address the spatio-temporal mismatch between supply and demand. This flexibility could be partially met with increasing grid capacity [5]. In addition, relying on renewable energies in the heating sector implies the use of biomass, synthetic fuels or direct electrification. With the exception of biomass, these result in increased electricity consumption [6] and, if not scheduled properly, could further increase the demand for flexibility. However, sector coupling through electrification can also be a source to provide flexibility. For instance, demand response (DR) enables system serving scheduling of power-to-heat (PtH) appliances like heat pumps and power-to-gas (PtG) applications such as electrolysers that can provide flexibility [7].

The increasing interconnectedness of energy sectors in the future energy system might yield flexibility options, but it also increases the complexity of assessing a cost-efficient energy transition, that entails all energy sectors and fully utilises the flexibility intrinsically available in the energy system. In this regard, energy system models can assist in the design and evaluation of future energy systems [8]. Furthermore, optimisation-based models provide decision support, by finding optimal solutions with regard to a target function, often being the minimisation of cost or emissions of a specific energy system [9]. The focus of investigation has historically been on the power sector, but is recently shifting towards models encompassing more than one sector. This is especially relevant not only because emissions arising from all sectors have to be mitigated simultaneously, but also, because there might be synergies in decarbonising the energy system as a whole as opposed to otherwise separately analysed sectors [10]. For instance, one such synergy lies in the above-mentioned additional flexibility, that can be provided to the electricity sector by the residential sector through demand side management (DSM) as well as PtG and PtH applications [7]. The extent to which this flexibility can be provided and efficiently utilised is only recently beginning to be researched. In this regard, Salpakari and Lund [11] analyse energy flexibility on a building level, finding that thermal and electrical energy storages combined with heat pumps provide more cost-efficient flexibility than other shiftable appliances. However, heat demand remains exogenous to the optimisation. Similarly, Wu et al. [12] implemented incremental building renovations in their model, deriving cost optimal renovation strategies for different housing types. Their findings indicate low cost decarbonisation options, but heat demands are simulated in a prior step and are therefore exogenous to the optimisation itself, which may leave room for additional flexibility.

An early approach that implements heat demand as a decision variable of an energy system model was developed by Brahman et al. [13], by enabling the temperatures of the heating system and indoor nodes to be controlled by the optimisation. It integrates rooftop PV and entails optimal scheduling of dispatchable units for generating heat or cold as well as thermal energy storages (TES) and vehicle to grid (V2G) integration, which were found to yield the greatest cost savings. Similarly, a more nuanced model for single family houses (SFH) was developed by Sperber et al. [14], in the form of five reduced order models of increasing complexity. Here, the internal heat capacity of building structure and interior air are regarded as ”passive thermal storage” that could yield large flexibility potentials for the electricity grid. Similarly, Rasku and Kiviluoma [15] analysed the effects of flexible residential heating on the Nordic power system and found that PtH along with thermal storages in the residential sector can be of lower cost than energy efficiency improvements if sufficient amounts of VRE are installed.

Regarding PtG, most models entailing this flexibility option provide detailed analysis of the energy system at large [16] and often focus on the flexibility provided solely by generating power to gas, but do not consider the downstream demand side possibilities of utilising the generated gas to supply heating demand [17]. In conjunction with the heat sector, PtG with hydrogen has been neglected historically [18] although some studies point out, that hydrogen and fuel cells could play a non-negligible role in heat provision for future energy systems [19]. Furthermore, relying on existing gas infrastructure might prove beneficial, especially in the residential sector, since a similar level of service can be provided by switching out the fuel [20]. In this realm, Longoria et al. [21] analyse the effects of hydrogen in the residential heating sector using an optimal power flow model that encompasses the Irish power system by incorporating electrolysers and increasing shares of hydrogen in the natural gas network. Nastasi et al. [22] developed a model to distinguish between houses, which require low and high temperature heat, that can be met via heat pumps and synthetic fuels respectively. Here, too, hydrogen is infused into the gas grid. Hence, re-electrification of hydrogen with fuel cells and the tradeoff between this technology and utilising hydrogen-enriched natural gas cannot be analysed.

It is therefore evident, that although several approaches exist to analyse flexibility, approaches that entail endogenous heat demand are sparse and rather recent developments. Furthermore, the utilisation of hydrogen in residential heat supply is not well researched yet. A research gap exists, regarding a combination of models that can both determine heat demand endogenously facilitating optimal temperature control from an energetic point of view and hydrogen technologies to provide heat on a building level.

To address this shortcoming, this work aims to develop a lumped capacitance[1] model for buildings within an energy systems optimisation framework. This allows for the system to utilise the flexibility originating from the controllable indoor and building structure temperature, while also including building refurbishments, electrolysers and fuel cells for seasonal renewable energy storage. The latter address the flexibility issue directly and are a means to sector coupling, since fuel cells not only provide electricity in the winter but also heat, which is usually discarded as waste heat. Furthermore, this approach lends itself to be used for system-wide assessment of larger energy systems in the future.

The rest of this work is structured as follows. First, the methodology is outlined and the lumped capacitance building model is described in chapter 2.1, briefly detailing underlying simplifications and assumptions about structural components. The model is then applied to and validated with a dataset of individual buildings in order to classify the resulting heat demands on a building level. Afterwards, electrically connected buildings are aggregated in chapter 2.2. In chapter 3 the results of the scenario analysis are shown and a sensitivity analysis for varying H_2 prices and varying lower temperature limits is appended in chapter 3.2. Results are discussed in chapter 4 and a summary and a conclusion are given in chapter 5.

[1] Note that some use the terminology of "RC"-models, highlighting the similarity between heat transmission and electrical energy flow in networks with resistors and capacitors. The model developed here would be a 3C2R model, entailing three nodes with heat storage capacity, and two resistances to heat flow.

2. Methodology

In order to build a model of connected houses, the energy systems modelling framework Backbone [23] was used. It allows the description of arbitrary energy systems as a combination of grids, nodes and units. A grid is defined as a layer in which a specific type of energy can be transferred between nodes. Nodes can store energy and be connected to other nodes via directed or uncontrolled energy flows. Directed energy flow can be used when modelling electricity systems, whereas uncontrolled flow can be used for modelling heat transfers. Furthermore, units are used to convert energy between grids. This flexibility allows for the modelling of energy systems containing several energy carriers, and is therefore well suited for modelling energy systems integrating multiple sectors. In this work, the energy carriers electricity, heat, natural gas and hydrogen are implemented. In a first step, the model will be outlined and validated for individual buildings using real annual heat demand data from an urban residential area within the municipality Bochum[2], for which data were provided by the municipal distribution system operator Stadtwerke Bochum [24]. Subsequently, aggregation of electrically connected buildings to a final model will be pursued.

[2]Bochum is one of the urban centres in the Rhine-Ruhr Metropolitan Region within North Rhine-Westphalia, Germany, one of the most densely populated areas in Europe

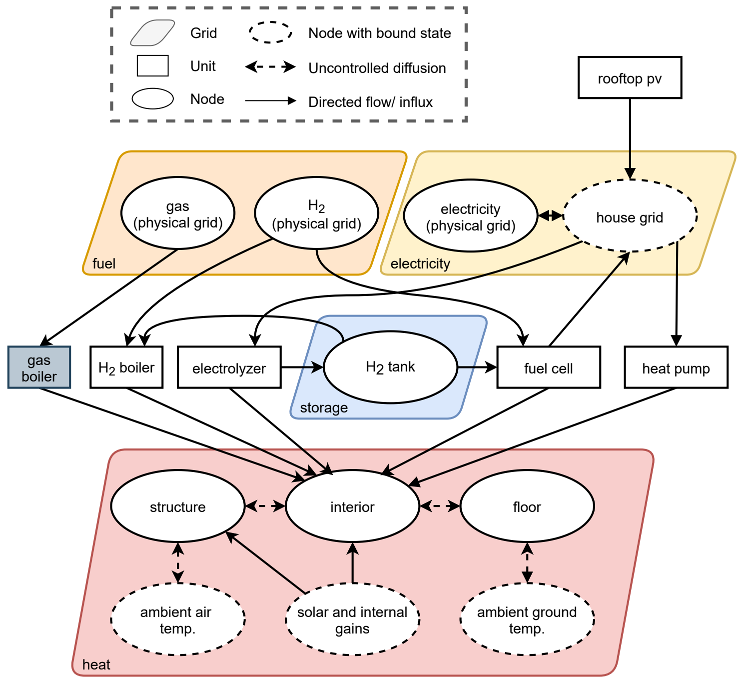

Figure 1: Schematic representation of the building model. Note that the gas boiler is the only unit present in the model from the beginning. All other units can only be utilised upon investment.

2.1. Lumped capacitance building model

2.1.1. Thermal building model

The methodology of Rasku and Kiviluoma [15] is used to describe the building via connected nodes in a heat grid. As displayed in Figure 1, the structure, interior, and floor nodes represent the building and are connected to each other and the environment, which is simplified to the ambient air and ground temperature. Connections between these nodes represent a flow of energy that cannot be controlled by the model. Instead, the rate at which heat flows is determined by the temperature difference between these nodes, and diffusion coefficients that are determined by surface areas and U-Values of the corresponding components. Temperatures for the ambient air and ground are taken from a local weather station [25]. Solar and internal gains as well as heat capacities of nodes in the heat grid are calculated according to a standard, which are based on the buildings' footprint area [26]. The transmission coefficient for the floor node is calculated using the methodology of Kissock et al. [27]. To calculate heat transmission coefficients for the interior and structure nodes, weighted average U-values were generated, using structural U-values for walls, windows and roofs of German buildings from the EU Building Stock Observatory for each decade. These were combined, after minor modifications to adjust for different temporal references, with statistical data from a local municipality containing a distribution of buildings built in the respective period [28, 29]. The used values are presented in Table 1

The present data for the specific buildings consisted of the buildings' footprint and living area and space, as well as water heating demands. However, in this work, only the space heating demand is considered. The number of floors, with an assumed height of 2.5 m, was estimated by dividing the living area by the floor area. In order to simplify the data acquisition and following calculations of solar gains and solar PV capacity factors, several simplifications were made regarding the buildings' representation in the model. For instance, the orientation of buildings was set to be north aligned, and a square footprint was used. Flat roofs are another simplification such that rooftop area is equal to the buildings' footprint. This enables the calculation of building envelope areas, which can then be combined with the weighted U-Values to obtain the final heat transmission coefficients. Since U-Values are a measure of how much energy is transmitted through a certain structural element, but the structural element itself has a heat capacity, the transmission of heat into the element has to be accounted for. This is achieved by splitting and doubling the U-Values of the floor and structure nodes.

	U-Values $[\frac{W}{m^2 \cdot K}]$		Heat capacity $[\frac{Wh}{m^2 \cdot K}]$
	Stock [28, 29]	Refurbished [30]	Both cases [26]
Walls	1.246	0.24	-
Windows	2.676	1.30	-
Roof	0.915	0.24	-
Floor node	0.34*	0.30	31.11
Structure node	-	-	45.83
Indoor node	-	-	2.78

Table 1: U-Values and heat capacities of building components used to parametrise the model. Since the actual parameters for the nodes are diffusionCoefficients in $[\frac{W}{K}]$, they are multiplied with the respective area. In the case of the structure node, a weighted average is used. The value for heat transmission through the floor was derived with the methodology of Kissock et al. [27]. Heat capacities are per square meter of footprint area.

2.1.2. Energy demand and supply of the building model

The thermal model of the building, as described in the previous chapter, yields a heat demand. In addition, with an electrical load, this completes the demand side of this model. Both of these demands can be met through different ways.

Heat demand occurs, based on the nodes' temperatures that are connected to the interior air node, whose temperature is constrained to fall into the range of 15-35 °C. In the case that the ambient temperature is higher than the interior temperature, heat flows into the building, whereas in the opposite case, heat flows from the interior node into the connected nodes, until the lower limit is reached, and heat must be supplied by heat generating units. Heat can be supplied to the interior node through a variety of ways. For instance, gas boilers can supply heat, that are assumed to be present in buildings using gas from a utility gas grid, since no data was available for existing heating technologies. Additionally, electrolysers can be used to generate hydrogen, and simultaneously supply the generated waste heat to the interior node. Generated hydrogen can then be used to either power a fuel cell, that generates electricity and heat, or to be burned in a retrofitted gas boiler. Additionally, heat pumps can be used for which time series for hourly COPs were obtained from an openly available dataset [31].

The electricity demand for the house grid node is determined through random assignment to one of 11 household profiles in an openly available dataset [32]. This demand can be met by electricity generated by rooftop PV, by converting hydrogen to electricity via a fuel cell, or through importing electricity from the physical electricity grid. As for rooftop PV, half of the buildings' floor area is assumed to be the available area for solar PV.

Regarding investment costs for technologies analysed in this work, a summary of parameters is given in Table 2 relating to 2020.

	Investment cost	**FOM cost [% of invest]**	**Lifetime [a]**	**Efficiency [%]**	**Annuity factor [-]**
Solar PV	1290 $\frac{€}{kW}$	1,70	27	17	0,0757
Gas boiler	97 $\frac{€}{kW}$	2,70	20	90	0,0872
Heat pump (air)	577 $\frac{€}{kW}$	1,00	19	time series	0,0896
Electrolyser	1295 $\frac{€}{kW}$	3,50	15	71	0,1030
Fuel cell	1684 $\frac{€}{kW}$	3,80	14	50 (el), 34 (th)	0,1076
H_2 Storage	10 $\frac{€}{kWh}$	2,30	23	-	0,0813
Refurbishment	400 $\frac{€}{m^2}$	-	50	-	0,0634

Table 2: Cost parameters of technologies in the model based on Petkov and Gabrielli [33] and refurbishment costs based on dena [30]. Refurbishment costs are per m^2 of living area. Annuities are based on lifetimes and an assumed cost of capital of 6 %. Electrolyser system efficiency of 71 % is assumed to be split into 60 % electrical and 11 % thermal efficiency.

2.1.3. Model validation

Since the target function of Backbone is to minimise cost and any energy supply incurs cost, heat that is supplied to the indoor node should also be the minimum amount of energy required to satisfy the lower temperature limit. Therefore, it can be interpreted as heat demand, which is plotted against the provided heat demand data in Figure 2 to be able to classify the results of the developed model. The annual heat demands display a decent correlation, although a positive offset can be observed for the values derived from the standard. This correlation appears not to be affected by the building type. Therefore, diffusion coefficients and heat capacities were varied between 70 % and 130 % of the standard values to investigate their effect on the final heat demand. Reducing diffusion coefficients can be seen as a building refurbishment.

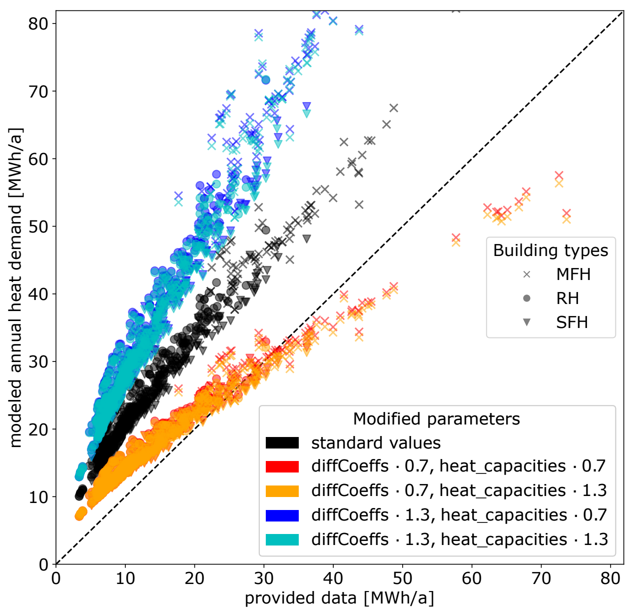

Figure 2: Annual heat demands of all residential buildings. Results of the model are on the y-axis and provided simulated heat demands are on the x-axis.

As expected, a variation of the U-Values had a rather large influence, whereas a variation in heat capacity had only negligible effect on the heat demand. This is to be expected, since U-Values and heat capacities can be interpreted as measure of energy loss to the environment and energy storage capacity respectively. However, with increasing heat demand, for both the reduced and increased U-

Values, deviations from the supplied data seems to increase faster than for the standard values for increasing heat demands. Furthermore, the provided data itself is only the result of a simulation. Thus, a fit to this dataset was not carried out. Instead, standard values were kept for further modelling of the entire quarter.

2.2. Aggregated model

Since the model representation of each building consists of several nodes and multiple decision variables, it was found that modelling the entire quarter in this level of detail was unfeasible. Therefore, an aggregated model was built, combining data of houses and the underlying electricity grid. The intersection of individual house data and electricity network data resulted in roughly 130 connected houses, which had to be further aggregated as described in the following.

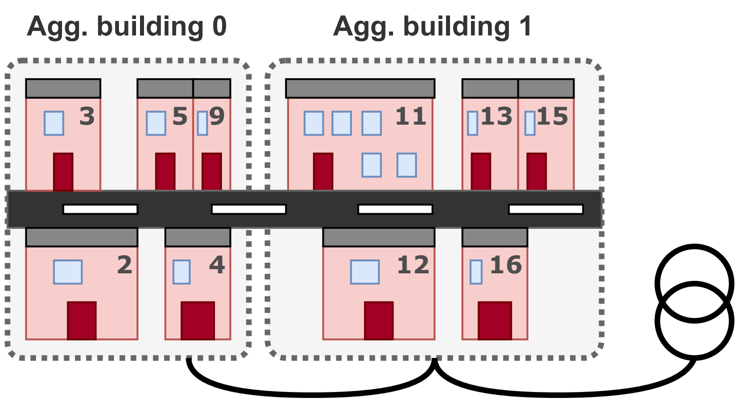

Figure 3: Schematic representation of the aggregation by tens, displaying two exemplary building aggregates. Within aggregated buildings an addition of the areas of windows, walls, roofs and floors was carried out to calculate the parameters for the thermal nodes and heat transmission (see Fig. 1). Furthermore, electrical connections between the buildings' electrical nodes and a node representing a transformer are added, which now serves as an electricity source.

2.2.1. Aggregation

Since the focus of this work is to analyse seasonal and diurnal effects of H_2 utilisation, an hourly temporal resolution of a full year was kept. Spatial aggregation was pursued, based on the street names and house numbers, as this allows for simple aggregation while maintaining spatial-coherence and might enable further analysis of the underlying electricity grid in the future. More precisely, all houses of the same tens were aggregated as displayed in Figure 3, reducing the amount of aggregates to 22. To determine the parameters for the aggregates, floor, living and wall areas were summed up as these are used to calculate solar and internal gains as well as heat capacities, which were then recalculated. Since this also changed the ratio between wall and floor area of an aggregated building, the weighted U-Values were updated accordingly. Finally, the electricity demand of the aggregates is also the sum of the electricity demand of the individual buildings.

2.2.2. Scenarios

To generate insights into how the simultaneous utilisation of both heat pumps, fuel cells and electrolysers affects the decarbonisation of the building sector, scenarios with varying emission reduction targets and assumptions about cost parameters were defined. In this regard, the German government envisions a reduction in carbon emissions of roughly 20 % and 40 % by the years 2025 and 2030, respectively. Since no actual data of the current building emissions is available, the model is run without constraining emissions, resulting in a cost-minimal solution, which will be used as a base case relative to which emission limits are applied. Furthermore, two alternative cost cases for the option making use of a gas boiler retrofit for hydrogen combustion are used, since cost data about boiler retrofits are unavailable. Here, a "zero cost" and a "high cost" retrofit are implemented in an attempt to cover a large range of possibilities. The former adheres either to modern appliances that are H_2 ready and do not require a retrofit, or to high government subsidies that suffice for the retrofit such that the household effectively has "zero cost". The "high cost" retrofit alternative uses cost for a new ordinary boiler (see Table 2), which might correspond to very old appliances that need to be replaced. Finally, the addition of an unconstrained scenario with a refurbished building shell yields a total of 8 scenarios with varying emission limits and the two cost cases for the H2-boiler retrofit. The parameters that change between the scenarios are summarised in Table 3.

Future hydrogen prices in the literature mostly represent levelised generation cost that are not facing the end consumer. However, since hydrogen is a gaseous energy carrier, a household-surplus-cost-factor was derived from the average consumer gas price and the average wholesale price for gas futures of 2020. The resulting factor was then multiplied with the levelised generation cost of hydrogen from Bukold [34]. However, since this method might overestimate the actual cost, a sensitivity analysis for hydrogen costs is carried out in chapter 3.2.

Parameter		**2020**	**2025**	**2030**	**Sources**
Emissions $[\frac{g_{CO_2}}{MWh}]$	Electricity	*408	300	200	[35, 36]
	Gas	185	185	185	[37]
	Hydrogen	0	0	0	Own assumption
Price $[\frac{€}{MWh}]$	Electricity	300	300	300	Own assumption
	Gas	60	60	60	[38, 39]
	Hydrogen	714	552	390	[39, 34]
Emission constraints		No CO_2 cap	80% of 2020	60% of 2020	[2]

Table 3: Parameters of the model for scenarios based on different years. The carbon intensity for electricity in 2020 was reduced due to the pandemic. Therefore, a value from 2019 was used. The refurbished scenario uses parameters of 2020.

The emission limits are applied as a global constraint to the entirety of emissions in the system. Thus, a decreased emission cap is expected to change the system composition towards a more renewable energy supply. This could be achieved through solar PV, which has no adhered emissions in this model and could be used with heat pumps to provide low carbon heat, thereby replacing the need for gas boilers. The model can invest in all technologies listed in Table 2 and schedule the units to satisfy both electricity and heat demands. Note that for 2025 and 2030 an annual cost reduction of 4 % is applied to the investment costs of technologies, which is a rather conservative estimate, since historically cost for low carbon technologies have decreased roughly exponentially at a 10 % rate [40].

3. Results

The resulting scenarios are named after the corresponding year and the cost case for hydrogen boiler retrofit, which is abbreviated as "zc_h2b" and "hc_h2b" referring to "zero cost H_2 boiler" and "high cost H_2 boiler" respectively. A building refurbishment is shown as "refurb." in the scenario names. The scenarios are evaluated in terms of system composition, energy provided per unit and total system cost for each scenario. The unconstrained model resulted in 328 t CO_2 emissions, from which the other scenarios are defined with the corresponding emission caps.

3.1. System composition and Energy supply

In terms of system composition, the emissions restriction leads to an increased deployment of solar PV, electrolysers, fuel cells and hydrogen storage. In the scenario of 40 % emissions reduction compared to 2020, which is the target for 2030, large quantities of solar PV are built, since these can provide emissions-free electricity disregarding life cycle emissions. Figure 4 shows this trend and also that more solar PV is built in the refurbished scenario. However, this is due to the fact that the refurbished houses needed air conditioning in order to remove excess heat in the summer, which requires electricity and coincides well with the availability of PV units. All hydrogen technologies are only being invested in once emissions are restricted.

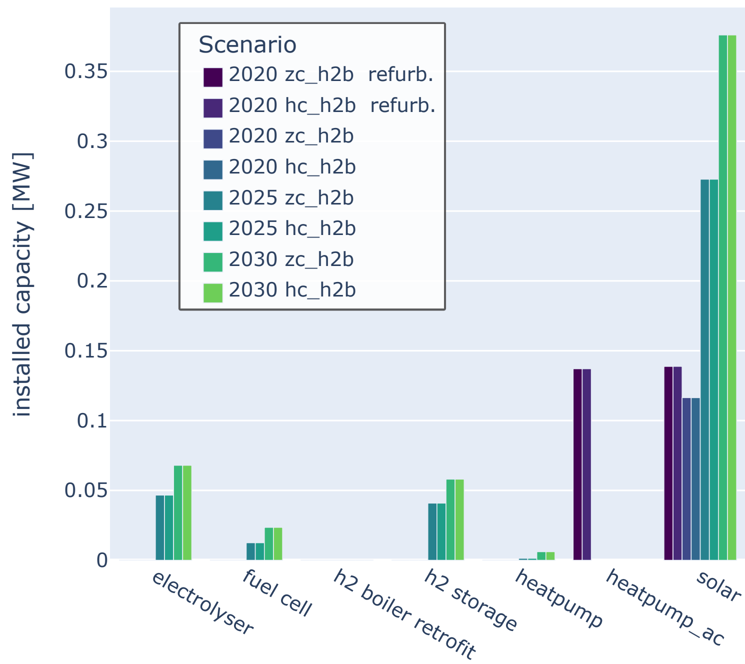

Figure 4: Total installed generation and storage capacity per unit type for all scenarios.

Although it was initially thought, that the combustion of hydrogen might be a cost-efficient alternative to reducing emissions in comparison to expensive building refurbishments, this could not be proven. On the contrary, the possibility to utilise hydrogen as fuel for a retrofit as a means to provide heat was never used. Thus, whether the H_2 retrofit had adhered cost didn't affect the results in any significant way. Since this has been the case for all evaluations in this regard, the "zero cost" alternative is excluded from the following figures.

Regarding energy supply in the respective grids, reveals that the scenarios yield results that are in line with the results from the installed capacities. For instance, stricter emission limits lead to decreased utilisation of gas boilers while technologies such as solar PV, heat pumps and hydrogen technologies are favoured. Although this could be a continuum, there are two exceptions to it. First, the cost structure in the 20 % emissions reduction scenario appears to impede electricity import, which is used to a lower extent than in the further restricted scenario of 2030. However, this is most likely due to a further reduction in the carbon intensity of grid electricity. The second exception is that the refurbished scenario uses more solar energy. However, this is due to the necessity of cooling in the summer.

Although Figure 4 suggests, that heat pumps are hardly used in the model, this is due to their high efficiency compared with other technologies. As they supply a high share of heat in the emissions-constrained scenarios, heat pumps are a relevant source of heat in this model, as can be seen in Figure 5.

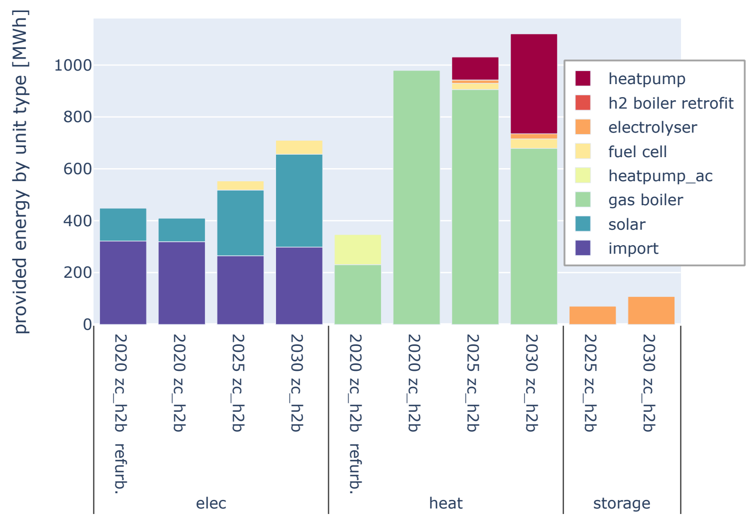

Figure 5: Energy generation for each grid by unit type

With regard to the cost of each scenario, as displayed in Figure 6, the costs for refurbishment dwarf the cost for investment in other technologies. The cost of the other models increase only slowly, but the composition of costs changes as less gas is being imported, and more investments into low carbon technologies are pursued to meet lower emission limits.

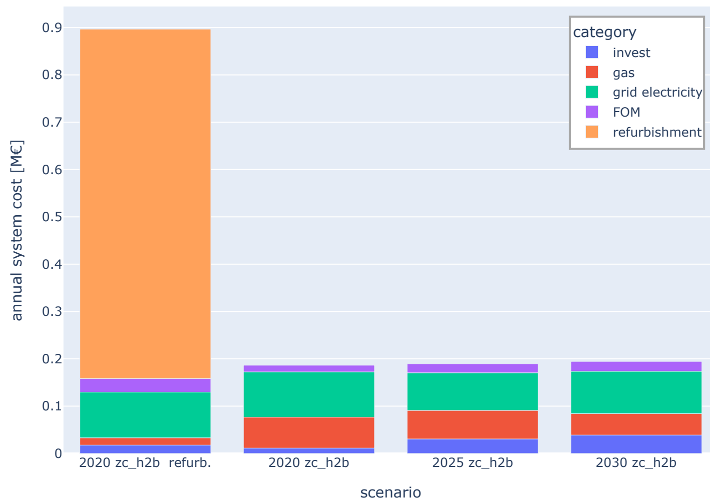

Figure 6: Annual system cost for the modelled scenarios. Note that costs for refurbishment were applied after the model was run.

An interesting effect occurred in the most restricted scenarios, where the building was used as a thermal energy storage, which is evident from the indoor temperature profile and the scheduling of heating technologies in Figure 7. This effect appears to occur to a larger extent with increasing price for heat provision as will be shown in Chapter 3.2. The aggregated building is being heated by the heat pump during morning hours, and the temperature drops once a sufficient level was reached for maintaining the temperature above the lower limit throughout the rest of the day. Furthermore, in the period displayed, the electrolyser is used during daytime and the fuel cell is used at night.

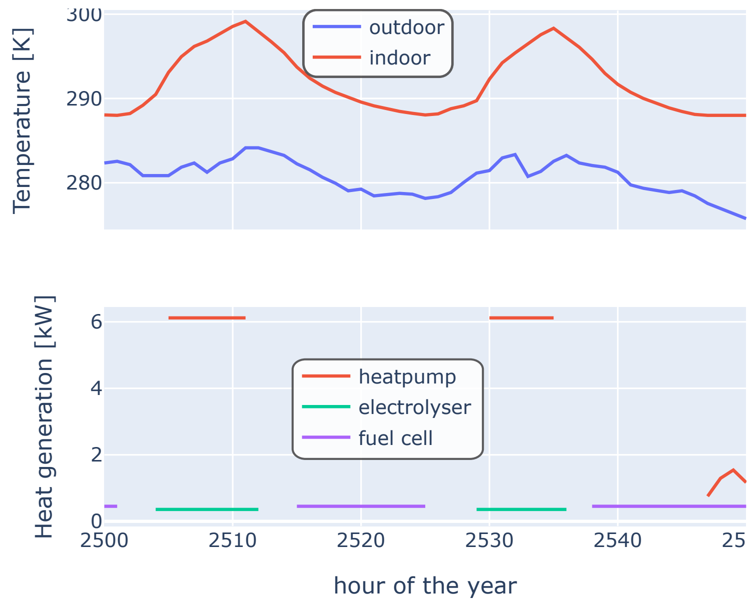

Figure 7: Temperature of an exemplary indoor node from the 2030 scenario and the scheduling of heat generating units over the course of two spring days.

Regarding emissions, emitted in each scenario, the refurbishment proves to be the most successful measure. However, it is also the most expensive route to avoid emissions, as Figure 8 shows. The avoidance costs are calculated by dividing the difference in emissions to the base scenario by the total annual cost displayed in Figure 6. While the amount of emissions is close for the refurbished scenario and the 60% allowed emissions scenario, it has to be kept in mind, that the reduction in emissions from grid electricity are mostly due to the reduced carbon intensity and not in the reduced import amount thereof. Although it has been stated, that thermal renovations of existing homes are the cheapest way to reduce CO_2 emissions [41], the results of this work do not support that statement.

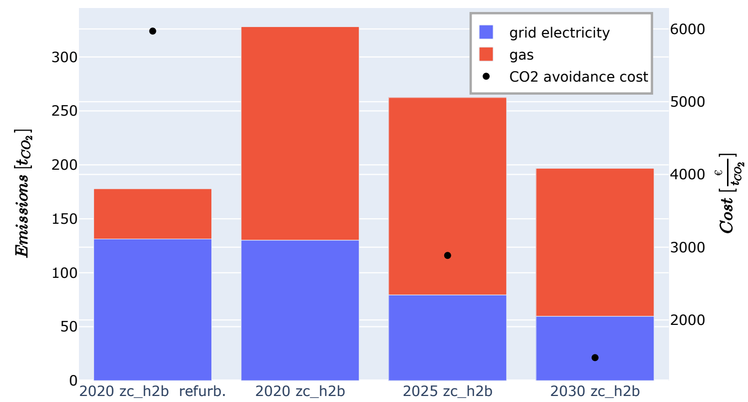

Figure 8: Annual CO_2 emissions per scenario as bars (left y-axis) and specific avoidance cost as black dots and (right y-axis).

3.2. Sensitivity analysis

Two parameters in the model are subject to great uncertainty and might influence the model results in a significant way. First, the selection of boundary temperatures of the indoor temperature, especially the lower boundary, was arbitrary and is highly dependent on user behaviour. Second, the calculation of hydrogen prices depends on modelling results, that are themselves highly uncertain. To address this issue, two sensitivity analyses are carried out, varying the lower temperature limit and hydrogen prices. The base model is the 2030 "high cost" scenario. The effects on system cost composition and energy provision for the resulting values are laid out in the following.

3.2.1. Sensitivity to lower boundary temperature

While initially the lower boundary temperature was set to 15 °C this constraint is increased in 1 °C steps up to 26 °C to investigate the occurring changes in the system due to this increased heat demand. The results show, that while the required energy increases with increasing lower temperature limit, the amount of gas used for heat provision is reduced. This allows for larger amounts of electricity imports, which are utilised to power heat pumps. This effect is shown in Figure 9, which also displays increased hydrogen generation, visible in increased amounts of energy supplied to the H_2 storage.

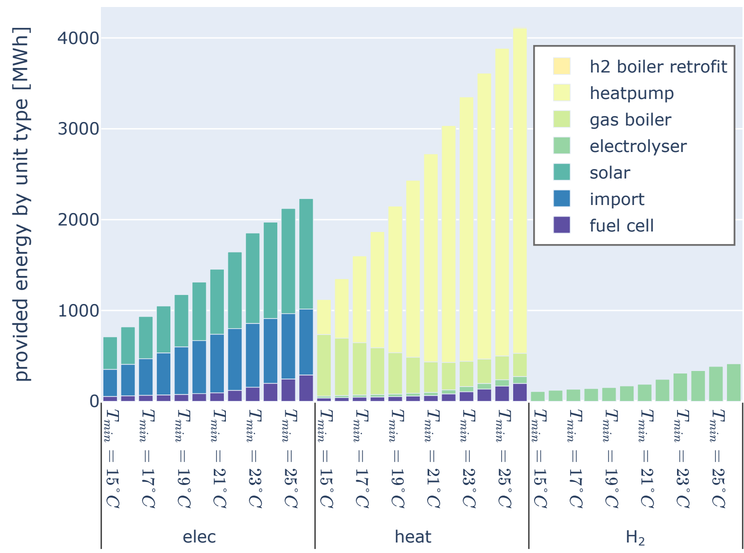

Figure 9: Energy provided to the corresponding grid via different units under varying lower boundary temperatures. Parameters of the 2030 "high cost" scenario are kept.

To meet the increased heat demand, larger amounts of technologies with no adhered carbon emissions are built as shown in Figure 10. In this regard, the increased temperature requirements result in a drastic increase in installed solar PV capacity and a smaller increase in electrolysers and hydrogen storage, although here, the increase is still greater than for fuel cells and heat pumps. Installed electrolyser capacity likely increases more than that of fuel cells or heat pumps to allow for immediate PtG utilisation of electricity generated with solar PV, which must occur in a shorter period diurnally, whereas fuel cells have a larger window to discharge the H_2 storage and thus require smaller amounts of installed capacity. The difference in the capacity increase between electrolysers and fuel cells can also be explained with the difference in efficiency of hydrogen generation and utilisation for heat provision. The efficiency of hydrogen generation is rather low when compared to the overall efficiency of heat generation from hydrogen when using fuel cells in conjunction with heat pumps. Although not visible, 500 W of H_2 boiler retrofit are built when the lower temperature limit is at 26 °C, which is the first occurrence of investment in this unit. This indicates, that for temperatures above 25 °C and with an emission cap of 60 % of 2020 levels, this model is not able to provide enough heat without combustion of H_2.

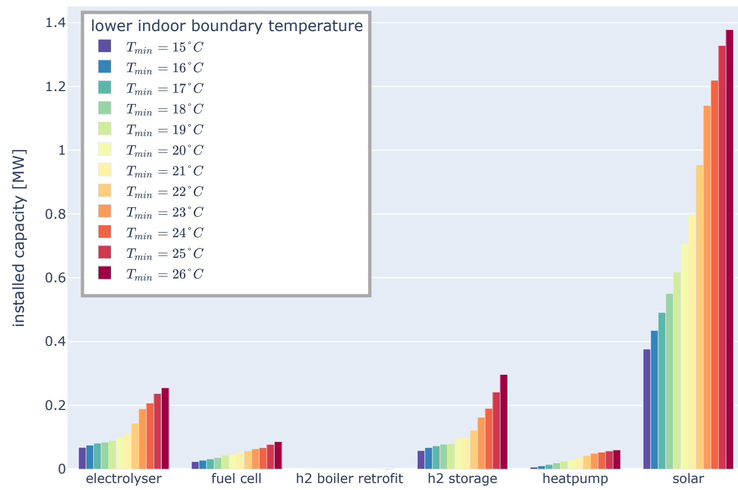

Figure 10: Installed capacity of units under varying lower boundary temperatures.

Regarding the cost structure in Figure 11 shows, that hydrogen imports are only required once the lower temperature boundary exceeds 23 °C and up to this temperature, hydrogen serves as fuel for heat pumps via fuel cells. Furthermore, it is evident, that costs scale linearly and the amounts of utilised gas in the system decrease with increasing temperature. Since the emission factor of electricity is only marginally higher than that of gas, but electricity can be used to generate heat at a higher efficiency via heat pumps, this method of heat provision is preferred by the model.

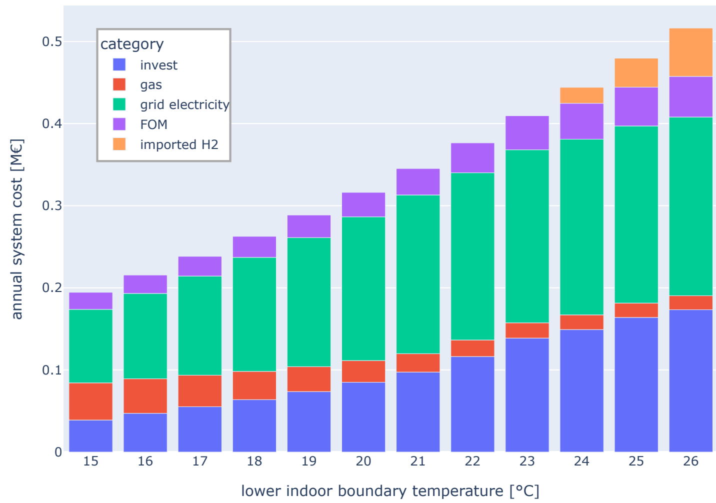

Figure 11: Total annual system cost under varying lower boundary temperatures.

3.2.2. Sensitivity to changing hydrogen prices

To further investigate what role hydrogen might play in residential heating, a sensitivity analysis was carried out for varying hydrogen prices. To do so, the parameters from the 60 % reduction scenario are kept, the lower temperature bound was raised to 22 °C and H_2 prices are varied from 600 to 30 $\frac{€}{MWh}$. With electricity and gas prices of 300 and 60 $\frac{€}{MWh}$ respectively, the resulting H_2 costs fall into three places: above electricity price, between electricity and gas price and below gas price. Costs for the boiler were applied in the shown scenarios, since almost no differences occurred when comparing the cost alternatives for the H_2 boiler. Regarding the "zero cost" alternative, only slight increases of H_2 boiler utilisation could be observed at very low hydrogen costs and are therefore not shown. Results for H_2 prices above 330 $\frac{€}{MWh}$ are excluded from the figures as well, since no differences were observable here.

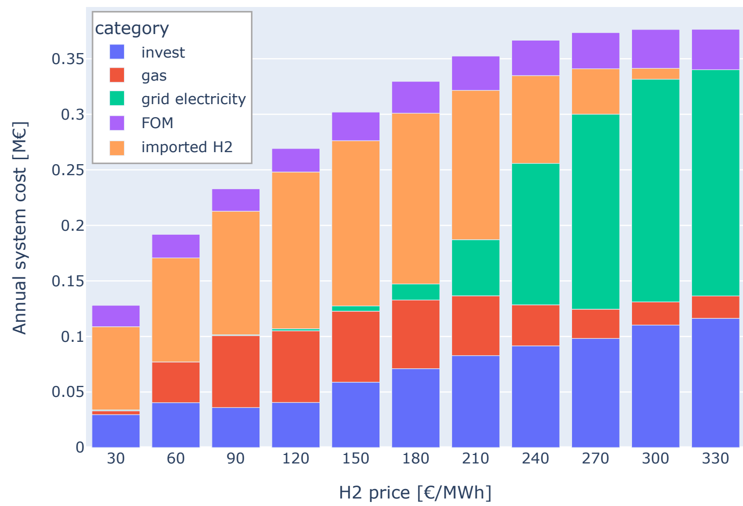

Figure 12: Total annual system cost under varying hydrogen prices.

When the hydrogen price reaches the gas price at 60 $\frac{€}{MWh}$, the emission cap is no longer a relevant constraint to the model, since the cost optimal solution achieves emissions of about 30 % of the base case. Emissions are almost entirely removed from the system at a price of 30 $\frac{€}{MWh}$, where large amounts of hydrogen are imported as shown in Figure 13.

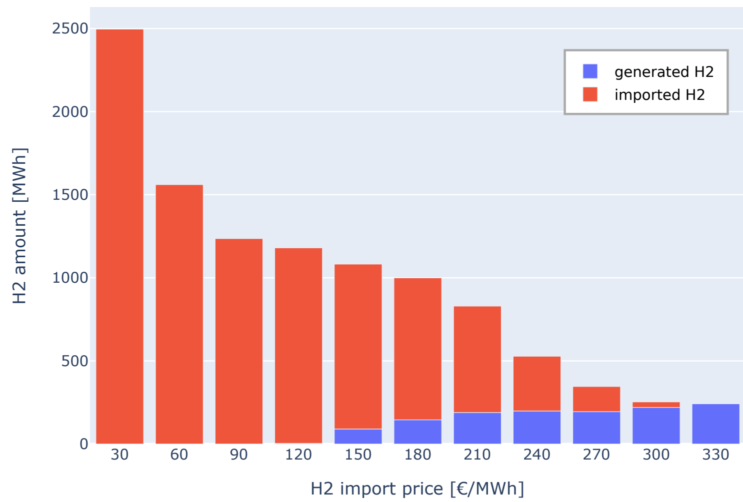

Figure 13: Imported and locally generated H_2. The change of these shares shows, that although cost share of H_2 imports of system costs decreases with decreasing H_2 cost, the amount of imported hydrogen increases.

The costs of the sensitivity analysis reveal, that with decreasing H_2 prices, electricity import decreases while gas and hydrogen imports increase. While increasing bar height indicates a higher share of total cost of imported hydrogen in Figure 12, it implies an even greater amount of hydrogen, since at lowering prices even equal bar height indicates increased amount.

The import of grid electricity is phased out when the price of imported H_2 reaches the electricity price. This trend is in line with fuel cell efficiency for generating electricity from hydrogen at 60%. Thus, electricity can be generated at lower cost from hydrogen at this price level. Also, for lower cost scenarios, no electrolysers or hydrogen storages are built.

The amount of imported gas peaks before hydrogen and gas reach price parity. At price parity, heat previously provided by gas boilers is partially provided by fuel cells, which is also evident from increased installed capacity as shown in Figure 14. When H_2 is available at half of the gas price, gas in the system is reduced to a negligible amount.

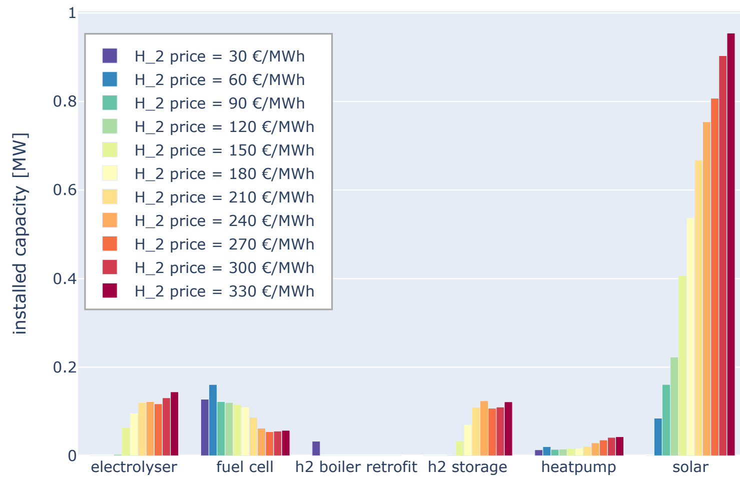

Figure 14: Installed capacities of different unit types under varying H_2 prices.

For a H_2 price of 30 $\frac{€}{MWh}$ the residential energy system consists almost exclusively of fuel cells, retrofitted H_2 boiler and heat pumps. The amount of installed fuel cell capacity, shown in Figure 14, drops with the price change from 60 to 30 $\frac{€}{MWh_{H_2}}$, since heat supply can be realised for lower cost when utilising cheap hydrogen and a retrofitted boiler. This can also be seen in Figure 15, where provided energy per unit type is detailed.

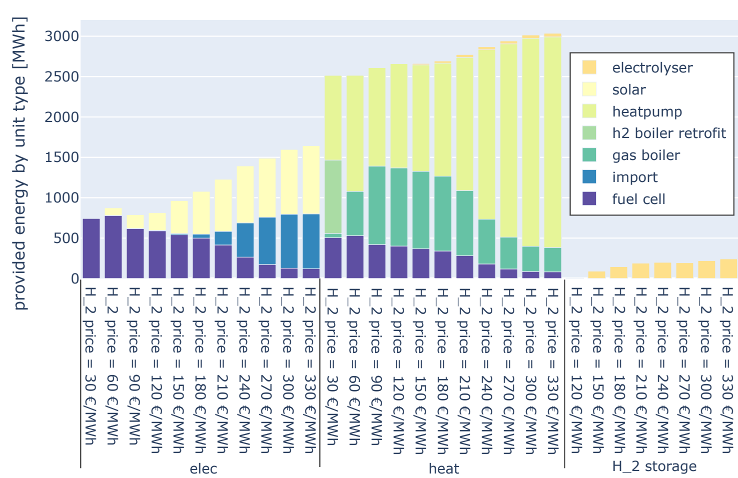

Figure 15: Energy provision in different energy grids under varying hydrogen prices. Only for hydrogen prices lower than that of gas (60 $\frac{€}{MWh}$) hydrogen is combusted for heat.

Decreasing H_2 prices first lead to increased utilisation of the gas boiler until price parity with natural gas is reached, and then H_2 is combusted directly for heat. This is likely due to the increased utilisation of fuel cells for electricity supply, reducing emissions from electricity supply, which allows for more emissions to be emitted elsewhere. Furthermore, the reduced electricity supply by solar PV indicates, that the electricity supply via fuel cells through low cost H_2 approaches price parity somewhere between 30 and 60 $\frac{€}{MWh}$.

The total amount of generated heat is reduced with reduced hydrogen prices. The reason for this is, that without a cheap and low carbon fuel to run dispatchable heat supply, heat demand is met by utilising solar energy when available to power heat pumps and "charge" the house. This "overheating" of homes or using them as thermal storages, which occurs in scenarios of higher cost H_2 is displayed in Figure 16. The temperature of the indoor air node is kept at the upper bound for several timesteps. This might seem counterintuitive at first, but it reduces the amount of energy needed during the night, because the structure of the building and the floor are heated up as well.

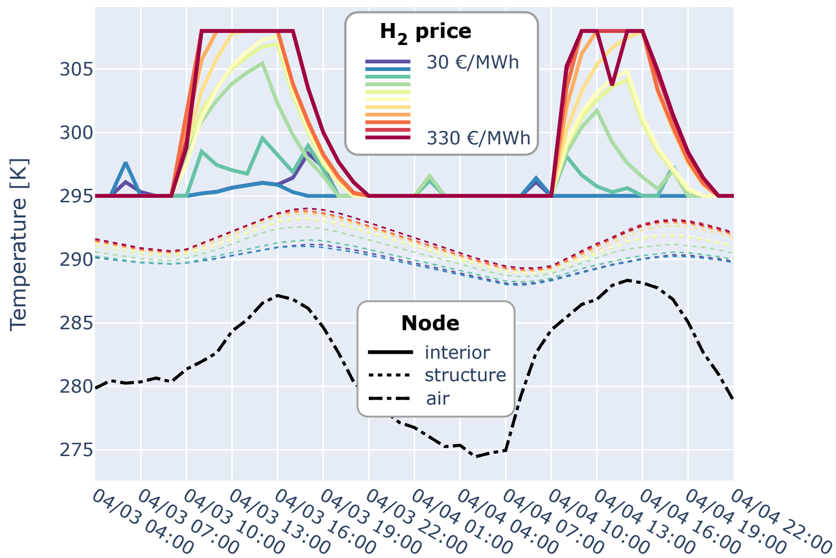

Figure 16: Temperatures at an arbitrary indoor and the corresponding structure node for different hydrogen prices. The outdoor temperature ("air"), doesn't change across scenarios. It shows, that higher H_2 prices lead to increased utilisation of thermal flexibility.

4. Discussion

The developed model is an abstraction of reality. As such, several simplifications were made, which entail shortcomings that will be discussed in this chapter. The limitations mainly focus on the technologies that can be used by the models and their implementation, and the thermal building model itself.

The technologies are implemented idealised, meaning that they can ramp up to their maximum power, or any other level thereof, within one time step, which is set to be one hour. Moreover, heating technologies directly supply heat to the indoor node, whereby real heat exchangers and associated losses are neglected. While heat exchangers might currently be represented by radiators in existing buildings, these would have to be replaced with e.g. floor heating when utilising low temperature heat provided by heat pumps. Additional costs for such measures are neglected as well as the fact that such heating systems not only supply heat to the indoor air but also to the structure to a certain extent. In the current implementation, the entire structure and indoor air are summarised as one node each, which might lead to increased heat demands for several reasons. First, there are unheated rooms in real buildings, that serve as insulation to the heated rooms and represent a portion of indoor air that must not be heated. Second, some parts of the buildings' structure are not in direct contact with the environment and might have significantly different U-Values for heat transmission through indoor walls/floors/ceilings. This is also true for the indoor node, accounting for the entirety of indoor air and furniture, which, in real buildings, are not all in contact with the floor of the building.

Furthermore, the actual COP of heat pumps is a function of the temperature gap between the temperature of the heat source and the target indoor temperature, but was implemented as a fixed time series here, which might distort the results. Additionally, heat pumps are subject to a special tariff in Germany, which makes them temporarily unavailable and changes the price for their electricity demand. Considering electrolysers, it remains questionable whether the utilisation of their waste heat in the summer is an efficient use of this energy. Current research shows, that reusing this energy increases the electrolysers efficiency [42], which might be a more efficient use thereof, especially since it is operated mainly in the summer, when heat demand is low. Furthermore, electrolysers in this model feed in to the H_2 without any compression. Thus, in order to adequately depict hydrogen storage in significant amounts, energy demands for compressing hydrogen would need to be added, or space requirements quickly become too large for domestic applications. Another technology that can already be seen as state of the art are short term batteries, which have not been included in this model.

Regarding the thermal building model, a quadratic building footprint was used for simplicity, which leads to a smaller surface to volume ratio than that of real buildings which are rather rectangular, and thus reduces the heat demand. In the case of single buildings, the heat demand should also be minimal, since the used optimisation framework minimises cost and thereby energy as long as energy utilisation implied additional cost. However, this model overestimates heat demands as was shown in Figure 2, which is evidence for a deviation between the derived and actual U-Values of the buildings. Also, the implemented temperature boundaries range from uncomfortably cold to uncomfortably hot. While this allows for the greatest flexibility, the extent to which this flexibility might become available in the real world greatly depends on individual preferences and consumer behaviour [7, 43]. Furthermore, the calculation of solar gains was pursued using the simplest of all possibilities, which assumes a fixed closing state of window blinds and two links between nodes in the heat grid were not implemented that exist in a real building. These are a connection between the interior and the outdoor node, representing ventilation and an influx from solar gains to the floor node, representing solar radiation incident on the building floor. Only space heating was analysed in this work, thus the resulting heat demand is an underestimation of actual final heat demand of buildings.

On a more general level, one limitation is the selection and implementation of weather data. Since only one year was used, the results cannot be regarded as robust. Also, the effect of wind on the cooling of the buildings' exterior was neglected. Furthermore, the emission targets of the German government have been used. Although these might be ambitious, even lower limits are required in order to limit the effects of climate change [44, 45]. Future studies should therefore analyse even stricter emission limits that are aligned with these goals.

The results of aggregated buildings do not coincide well with the aggregated heat demands of provided data. In contrast to the results of the individual building model, where heat demands were overestimated, heat demands in the aggregated model were underestimated. A reason for this might be the lower boundary temperature, which was reduced from 17 °C to 15 °C from the individual to the aggregated model. Nevertheless, the used aggregation methodology cannot be recommended without further investigations.

5. Conclusion and Outlook

In this work, a simple model was presented to integrate thermal energy demands into an energy system model and to assess whether hydrogen combustion or utilisation in fuel cells could play a role in decarbonising residential heating. To do so, several simplifications about the buildings' morphology were made. Buildings were then simplified to three interconnected nodes. Heat capacities for these nodes were derived from a national standard, and the indoor node, where actual heat demand occurs, was connected to heat providing technologies. The developed model was then run for individual houses, yielding a decent correlation regardless of the housing type (MFH/SFH) as shown in Figure 2. To be able to model a residential quarter, connected houses were aggregated to a model consisting of 22 aggregated houses.

Then, scenarios were defined by emission limits, cost reductions and building refurbishments. However, no investment in H_2 boilers occurred in any of these scenarios. While the refurbished scenario displayed the highest cost, it almost halves emissions due to the reduced heat demand. Additionally, it was found that, whenever a restriction is applied to dispatchable heat supply, which is the case with an emission cap for gas boilers, the buildings' internal heat capacity was used as a storage, to allow for higher utilisation of electricity generated with solar PV. While in this model, the boundaries were set to rather uncomfortable temperatures, this model capability might prove useful for future research investing system level effects of DR.

To investigate effects of varying lower indoor temperature limit that are subject to individual preferences and domestic hydrogen prices that are highly uncertain, sensitivity analysis was performed for both of these parameters while keeping the scenario parameters from 2030. This revealed that costs as well as required energy scale linearly with increasing temperature. The amount of gas used for heating is reduced to allow for more electricity imports and hydrogen generation, both of which are then utilised to power heat pumps. Hydrogen imports are only required once the lower temperature boundary exceeds 23 °C and up to this temperature, hydrogen serves as fuel for heat pumps via fuel cells. As expected, the quantity of utilised imported hydrogen increased with decreasing hydrogen prices. Here, reducing emissions from heating ceases to be an issue as soon as hydrogen prices reach the price levels of gas. Although currently a large price gap between these commodities exists, this gap might close with increasing carbon taxation, which raises gas prices, and large deployment of utility scale electrolysers, which reduces the H_2 price.

H_2 boiler retrofits are only utilised in two of the edge cases of the sensitivity analyses. As for the temperature, the retrofit is only utilised at a 26 °C lower limit. Even at this high value for a lower boundary temperature, the installed capacity is fairly small. The price sensitivity revealed, that only at a hydrogen import price of 30 $\frac{€}{MWh}$, a relevant contribution to heat supply is realised with H_2 boilers.

The mentioned shortcomings of the thermal building model could be addressed in many ways in the future. For instance, implementing a demand for and the capability to supply domestic hot water. Additionally, thermal as well as electrochemical energy storages could be included, in the form of readily available technologies such as hot water tanks and lithium-ion batteries respectively. This allows for in depth analysis of synergies between the heat and electricity sector as it is a more efficient diurnal energy storage and is likely to reduce the effect of overheating, which is most likely unacceptable from the point of view of consumers. In addition to the hot water storage, which is mostly installed along with a boiler, the radiators could be implemented in the model to allow for evaluation of necessary radiator surfaces as well as supply temperatures. The latter might then limit the choice of technologies, for instance in older buildings, and thereby make for a more realistic model. This would also address the issue, that heat pumps are not a suitable heating technology for all buildings, especially old and poorly insulated buildings.

It should also be emphasised, that incremental refurbishments, instead of refurbishing the entire building at once, might be efficient along the way towards deep decarbonisation. This could be investigated in the future by allowing investments in decreasing the U-Values of connected nodes in the heat network.

References

[1] Umweltbundesamt . Energieverbrauch privater haushalte — umweltbundesamt. 2018. URL: https://www.umweltbundesamt.de/daten/private-haushalte-konsum/wohnen/energieverbrauch-privater-haushalte#endenergieverbrauch-der-privaten-haushalte.

[2] BMU . Entwurf eines ersten gesetzes zur Änderung des bundes-klimaschutzgesetzes. 2021.

[3] DIW , Baake P, Duso T, Fratzscher M, Haan P, Kemfert C, et al. Heat monitor 2018: Rising heating energy demand, thermal retrofit rate must increase. 2019. URL: www.diw.de/newsletter_en. doi:10.18723/diw_dwr:2019-XX-X.

[4] dena . dena-gebäudereport kompakt 2019: Statistiken und analysen zur energieeffizienz im gebäudebestand 2019;.

[5] Tarroja B, Chiang F, AghaKouchak A, Samuelsen S, Raghavan SV, Wei M, et al. Translating climate change and heating system electrification impacts on building energy use to future greenhouse gas emissions and electric grid capacity requirements in california. Applied Energy 2018;225:522–34. doi:10.1016/J.APENERGY.2018.05.003; heating electrification requires up to a 31.6future grid capacity needs.

[6] Ruhnau O, Bannik S, Otten S, Praktiknjo A, Robinius M. Direct or indirect electrification? a review of heat generation and road transport decarbonisation scenarios for germany 2050. Energy 2019;166:989–99. doi:10.1016/J.ENERGY.2018.10.114.

[7] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity.

Renewable and Sustainable Energy Reviews 2015;45:785–807. doi:10.1016/J.RSER.2015.01.057.

[8] Lund H, Arler F, Østergaard PA, Hvelplund F, Connolly D, Mathiesen BV, et al. Simulation versus optimisation: Theoretical positions in energy system modelling. Energies 2017, Vol 10, Page 840 2017;10:840. URL: https://www.mdpi.com/1996-1073/10/7/840/htmhttps://www.mdpi.com/1996-1073/10/7/840. doi:10.3390/EN10070840.

[9] Horschig T, Thrän D. Are decisions well supported for the energy transition? a review on modeling approaches for renewable energy policy evaluation. Energy, Sustainability and Society 2017;7:1–14. URL: https://energsustainsoc.biomedcentral.com/articles/10.1186/s13705-017-0107-2. doi:10.1186/S13705-017-0107-2/TABLES/1.

[10] Chang M, Thellufsen JZ, Zakeri B, Pickering B, Pfenninger S, Lund H, et al. Trends in tools and approaches for modelling the energy transition. Applied Energy 2021;290:116731. doi:10.1016/J.APENERGY.2021.116731.

[11] Salpakari J, Lund P. Optimal and rule-based control strategies for energy flexibility in buildings with pv. Applied Energy 2016;161:425–36. doi:10.1016/J.APENERGY.2015.10.036.

[12] Wu R, Mavromatidis G, Orehounig K, Carmeliet J. Multiobjective optimisation of energy systems and building envelope retrofit in a residential community. Applied Energy 2017;190:634–49. doi:10.1016/J.APENERGY.2016.12.161.

[13] Brahman F, Honarmand M, Jadid S. Optimal electrical and thermal energy management of a residential energy hub, integrating demand response and energy storage system. Energy and Buildings 2015;90:65–75. doi:10.1016/j.enbuild.2014.12.039.

[14] Sperber E, Frey U, Bertsch V. Reduced-order models for assessing demand response with heat pumps – insights from the german energy sys-

tem. Energy and Buildings 2020;223:110144. doi:10.1016/J.ENBUILD.2020.110144.

[15] Rasku T, Kiviluoma J. A comparison of widespread flexible residential electric heating and energy efficiency in a future nordic power system. Energies 2019;12. doi:10.3390/en12010005.

[16] Welder L, Ryberg D, Kotzur L, Grube T, Robinius M, Stolten D. Spatio-temporal optimization of a future energy system for power-to-hydrogen applications in germany. Energy 2018;158:1130–49. doi:10.1016/j.energy.2018.05.059.

[17] Ge P, Hu Q, Wu Q, Dou X, Wu Z, Ding Y. Increasing operational flexibility of integrated energy systems by introducing power to hydrogen. IET Renewable Power Generation 2020;14:372–80. doi:10.1049/iet-rpg.2019.0663.

[18] Nastasi B, Basso GL. Hydrogen to link heat and electricity in the transition towards future smart energy systems. Energy 2016;110:5–22. doi:10.1016/J.ENERGY.2016.03.097.

[19] Chapman A, Itaoka K, Hirose K, Davidson FT, Nagasawa K, Lloyd AC, et al. A review of four case studies assessing the potential for hydrogen penetration of the future energy system. International Journal of Hydrogen Energy 2019;44:6371–82. doi:10.1016/j.ijhydene.2019.01.168.

[20] Dodds PE, Staffell I, Hawkes AD, Li F, Grünewald P, McDowall W, et al. Hydrogen and fuel cell technologies for heating: A review. International Journal of Hydrogen Energy 2015;40:2065–83. doi:10.1016/J.IJHYDENE.2014.11.059.

[21] Longoria G, Lynch M, Curtis J. Green hydrogen for heating and its impact on the power system. International Journal of Hydrogen Energy 2021;46:26725–40. doi:10.1016/j.ijhydene.2021.05.171.

[22] Nastasi B, Basso GL, Garcia DA, Cumo F, de Santoli L. Power-to-gas leverage effect on power-to-heat application for urban renewable thermal energy systems. International Journal of Hydrogen Energy 2018;43:23076–90. doi:10.1016/j.ijhydene.2018.08.119.

[23] Helistö N, Kiviluoma J, Ikäheimo J, Rasku T, Rinne E, O'Dwyer C, et al. Backbone—an adaptable energy systems modelling framework. Energies 2019;12(17):3388. doi:10.3390/en12173388.

[24] Bochum S. Stadtwerke bochum. 2021. URL: https://www.stadtwerke-bochum.de/impressum.

[25] DWD . Historische stündliche stationsmessungen der lufttemperatur und luftfeuchte für deutschland. 2018.

[26] Deutsches Institut für Normung e. V. . Energetische bewertung von gebäuden: Berechnung des nutz-, end- und primärenergiebedarfs für heizung,. 2018.

[27] Kissock K, Selvacanabady A, Raghavan N. Simplified model for ground heat transfer from slab-on-grade buildings. ASHRAE Transactions 2013;(119).

[28] EU . Eu building stock observatory: Eu buildings database. 2015. URL: https://ec.europa.eu/energy/en/eu-buildings-database.

[29] Ruhr R. Flächennutzung, bauen und wohnen: Monitoring für den größten ballungsraum deutschlands. 2017. URL: https://www.rvr.ruhr/daten-digitales/regionalstatistik/flaechennutzung-bauen-und-wohnen/.

[30] dena . dena-sanierungsstudie. teil 2: Wirtschaftlichkeit energetischer modernisierung in selbstgenutzten wohngebäuden. begleitforschung zum dena-projekt ñiedrigenergiehaus im bestand\: deutsche energie-agentur gmbh (dena),institut wohnen und umwelt gmbh (iwu)

2012;URL: https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9120_dena-Sanierungsstudie_Einfamilienhaeuser_Teil_2.pdf.

[31] Ruhnau O. When2heat heating profiles. ???? doi:10.25832/when2heat/2019-08-06.

[32] Synthetic sample electric load profile (three-phase) by household types (germany). 2020. URL: http://opendata.ffe.de/dataset/synthetic-sample-electric-load-profile-three-phase-by-household-types-germany/.

[33] Petkov I, Gabrielli P. Power-to-hydrogen as seasonal energy storage: an uncertainty analysis for optimal design of low-carbon multi-energy systems. Applied Energy 2020;274:115197. doi:10.1016/j.apenergy.2020.115197.

[34] Bukold S. Blauer wasserstoff. 2020.

[35] UBA . Entwicklung der spezifischen kohlendioxid-emissionen des deutschen strommix in den jahren 1990 - 2020. 2021.

[36] Fattler S, Conrad J, Regett A, Böing F, Guminski A. Dynamis hauptbericht – dynamische und intersektorale maßnahmenbewertung zur kosteneffizienten dekarbonisierung des energiesystems. ???? URL: https://openaccess.ffe.de/10.34805/ffe-144-19/. doi:10.34805/ffe-144-19.

[37] McCay AT, Feliks ME, Roberts JJ. Life cycle assessment of the carbon intensity of deep geothermal heat systems: A case study from scotland. Science of The Total Environment 2019;685:208–19. doi:10.1016/j.scitotenv.2019.05.311.

[38] Bundesnetzagentur . Jahresbericht 2020 märkte im digitalen wandel. 2020. URL: www.bundesnetzagentur.de/vorhabenplan.

[39] BDEW . Gaspreisanalyse november 2021 haushalte. 2021. URL: https://www.bdew.de/service/daten-und-grafiken/bdew-gaspreisanalyse/.

[40] Way R, Ives M, Mealy P, Farmer JD. Empirically grounded technology forecasts and the energy transition 2021;.

[41] Galvin R. Thermal upgrades of existing homes in germany: The building code, subsidies, and economic efficiency. Energy and Buildings 2010;42:834–44. doi:10.1016/J.ENBUILD.2009.12.004.

[42] Bilbao DC. Valorization of the waste heat given off in a system alkaline electrolyzer-photovoltaic array to improve hydrogen production performance: Case study antofagasta, chile. International Journal of Hydrogen Energy 2021;46:31108–21. doi:10.1016/j.ijhydene.2021.07.016.

[43] Huckebrink D, Bertsch V. Integrating behavioural aspects in energy system modelling—a review. Energies 2021;14. doi:10.3390/en14154579.

[44] Geiges A, Nauels A, Parra PY, Andrijevic M, Hare W, Pfleiderer P, et al. Incremental improvements of 2030 targets insufficient to achieve the paris agreement goals. Earth System Dynamics 2020;11:697–708. doi:10.5194/esd-11-697-2020.

[45] Rogelj J, Shindell D, Jiang K, Fifita S, Forster P, Ginzburg V, et al. Mitigation pathways compatible with 1.5°c in the context of sustainable development. Global Warming of 15°C IPCC Special Report on the impacts of global warming of 15°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change 2018;:92–174.