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Assessing the impact of local energy generation and storage to achieve the decarbonization of the single-family housing stock in Germany

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ABSTRACT

The decarbonization of the building stock, in this paper focusing on the single-family house typology in Germany, is essential to achieve the climate goals. In fact, as the largest part of the building stock, it represents more than 65 % of the entire German residential building stock. Current strategies and regulations have demonstrated low impact on carbon emission reduction due to poor renovation rates, particularly in the single-family house typology. The present study analyzes the potential of carbon emission reduction prioritizing local renewable energy generation and storage in combination with improved building energy systems. Through a simulation-based approach, it considers reference buildings of different age classes and formulates variants for improving strategies with different levels of retrofit, under the premise of a fully renewable, locally generated energy supply. Based on the potential for solar energy supply, the variants consider the seasonal shift that needs to be stored and particularly the role of hydrogen as an energy storage medium. The study goal is quantifying the impacts of the local renewable energy production, and its required storage capacity depending on the retrofit depth, for estimating the potential of transforming the single-family house stock to net zero carbon emissions.

1. Introduction

1.1. Motivation

The decarbonization of the building stock is essential to achieve the carbon neutrality targets imposed by the European Union (EU) and by national regulations [1]. In 2021, in the Federal Republic of Germany, the building sector caused 115 million tons of CO_2-eq. and missed its set target of 113 million tons of CO_2-eq. With around 12.9 million buildings, 66.5 % of the German residential building stock consists of single-family houses [2]. As such, the energy transition of this building category is essential for reducing emissions and achieving greenhouse gas neutrality through a combination of environmental compatibility, affordability, supply security and intelligent and innovative climate protection actions [3].

In past years, several national laws and strategies have been developed to achieve the decarbonization of the building sector: the two main strategic documents for reducing carbon dioxide emissions are the Energy Efficiency Strategy for Buildings (*Energieeffizienzstrategie Gebäude*) and the German government's National Hydrogen Strategy (*Nationale Wasserstoffstrategie (NWS)* der Bundesregierung) [3,4]. Their aim is to increase the use of renewable energies to cover energy consumption for electricity, heating and transport, as well as to increase energy efficiency and reduce primary energy demand by enhancing energy productivity. Renewable energies are used in the heat supply through heat pumps and power-to-X technologies. Latter offer the possibility of storing electrical energy in various states. The prerequisites for its use are adapted heating networks and storage systems. Current regulations assign priority to the building envelope's U-values, the degree of solar energy permeability and replacing existing heating systems for increasing the buildings' efficiency [3]. By increasing solar energy generation systems, such as photovoltaic panels and solar thermal collectors, the relevance of storing energy to guarantee supply despite the fluctuations and without overloading the grid, becomes crucial [4,5]. The use of hydrogen as a storage medium is among the potentially promising measures: hydrogen is used in a wide range of applications as an energy carrier and storage medium, in sector coupling, in the electricity sector and in the chemical, industrial and transport sectors through power-to-X processes. The *NWS* sees future potential in green, blue and turquoise hydrogen as low-carbon dioxide approaches to support the implementation of greenhouse gas

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neutrality. The goal of *NWS* is establishing hydrogen as an energy source, to further develop it in terms of economic efficiency and to expand and convert a suitable dedicated infrastructure. In the building sector, an application to generate heating supply is possible [4].

To integrate the idea of power-to-X technologies into single-family houses, there are various indicators to consider. The process of storing energy from locally generated electrical energy and its recovery is characterized by energy losses. The hydrogen production achieves 62 % of the supplied energy [6–8]. According to the system configuration, the electrical efficiency of the fuel cell during energy recovery is circa 31 % and the thermal efficiency of 18.6 % [9]. Approximately 50 % off losses are attributed to the entire process.

1.2. Problem statement

In the past decades, retrofitting strategies mainly focused on thermal insulation and heating system replacement. However, the overall annual modernization rate through increased thermal insulation in the period from 2010 to 2016 corresponded to 0.99 % of the entire German building stock.

The technical building equipment consists of three key components: the heating type, the main energy source for heating and the main heat generator. To date, 86 % of detached and semi-detached houses have centralized heating systems [2]. The main energy sources are natural gas and oil, covering respectively around 52 % and 30 % of the energy supply. Heat is generated predominantly using natural gas (48 % of households). The proportion of installed electric heat pumps is around 4 % and the use of combined heat and power units powered by oil, natural gas or biomass is 0.1 %. For the period under review, from 2010 to 2016, the annual modernization rate of building heating systems, including the connection to district heating networks for the single and two-family house stock, is around 3.1 %. The modernization rate for the entire residential building stock in the heat generator category is around 3.05 %. Overall, oil-fired boilers were predominantly replaced by other systems. A comparison between the use and replacement of heating systems shows that gas boilers, district heating or heat pumps are predominantly used [10].

To fulfil the goals of the energy transition, a further development and expansion of the networks is essential. The increasing use of locally generated renewable energies promotes an overload of the German electricity grid. This leads to countermeasures for the varying loads and production peaks, for example by expanding the grid or integrating energy storage systems [5]. Indeed, various sources address action in the building sector to achieve climate neutrality through a reduction in energy demand, electrical storage systems, power-to-gas, the use of energy converters and renewable energies [11,12,6].

1.3. Literature

This literature review looks at current developments, research approaches, technological advances and basic principles in the field of decentralized energy production and storage.

Over the years, studies have been carried out combining PV systems, heat collectors, heat pumps, short-term and long-term storage, employing the waste heat of the fuel cell to cover the hot water demand [13–16].

In 1996, the Fraunhofer Institute for Solar Energy Systems [13] presented the results of a research project on the implementation of hydrogen as a long-term storage medium. In this early project, they developed a building that covered the entire energy demand for space heating, hot water, electricity and cooking through a combination of PV system, heat collectors, battery, electrolyser, hydrogen storage and fuel cell. The study shows that hydrogen can in principle be used as a long-term storage system in single-family houses.

Another focus of various studies is the investigation of the economic efficiency of different variants. Knosala et al. [15] have prepared a cost analysis for the use of different heat generators – fuel cells, hybrid boilers and heat pumps – for single and multi-family houses in Germany taken from the TABULA tool. The analysis shows that hydrogen plays an important role compared to other heat generators, especially in regions with a high hydrogen supply or when heat pumps are not eligible. However, the combination of decentralized energy generation and storage has not been investigated. Based on the assumption that refurbishing the German building stock is not sufficient to achieve the climate targets, Huckebrink and Bertsch [17] investigated the decarbonization of the heating sector of residential buildings by electrifying it. Their economic evaluation shows that a combination of PV systems, heat pump and hydrogen is more cost-efficient than a comprehensive building refurbishment. According to Egeland-Eriksen et al. [18], it requires a critical examination of elaborated concepts and their performance for the use of hydrogen as decentralized storage in different building typologies. The study emphasizes the low energy efficiency, 15 % to 40 %, of the overall hydrogen supply chain for production and reconversion as well as the high acquisition costs.

Flexibility through decentralized energy generation and storage plays a key role in the decarbonization of the building sector. Aspects such as the combination of short-term and long-term storage [17,18], the generation of electricity and heat in the energy recovery of the long-term storage medium [14], the implementation of storage systems to balance demand and supply [19], sector coupling [15,19] and the switch from fossil gas to renewable energy [20] are considered.

The above sources provide some examples of practical applications in existing buildings and the interest in combining decentralized energy production and storage in different building typologies. Due to the increased use of waste heat for hot water demand, this study focuses on the interaction between heat pumps as decentralized energy producers and hydrogen as decentralized energy storage. The focus is on employing waste heat from the fuel cell in the cold months, when it is needed to increase in the performance of the air source heat pump for providing the heating requirements of selected reference single-family houses in Germany. Furthermore, the extent to which CO_2 emissions change under the premise of decentralized energy generation and storage has been discussed.

1.4. Approach

To address the outlined problem, this study examines the integration of decentralized energy generation options and energy storage located in buildings, considering the relatively high ratio between roof and heated surface in single-family houses and the general space availability for hosting storage systems. Due to their locations in low density neighborhoods, single-family houses are rarely connected to district heating networks and are not supposed to benefit soon of advantageous (in terms of carbon emissions) centralized energy supply systems. Therefore, the study analyzes the full potential of using roof surfaces for renewable energy and their local storage for own use, avoiding overcharging the grid.

While hydrogen is being discussed worldwide due to its low-carbon, energy-storing properties [4], this study examines it in a supporting function. First, it examines to what extent the use of hydrogen as a long-term energy storage system enables covering the energy requirements of selected buildings without deep retrofit measures such as increasing thermal insulation. Moreover, it analyzes which requirements in terms of additional storage capacity, form of local energy generation and space the buildings need, to become carbon neutral in operations.

2. Method

The present study examines the effects of integrating local energy generation and storage on selected building age classes of the single-family house typology using energy and greenhouse gas balances. Fig. 1 illustrates the study‘s workflow.

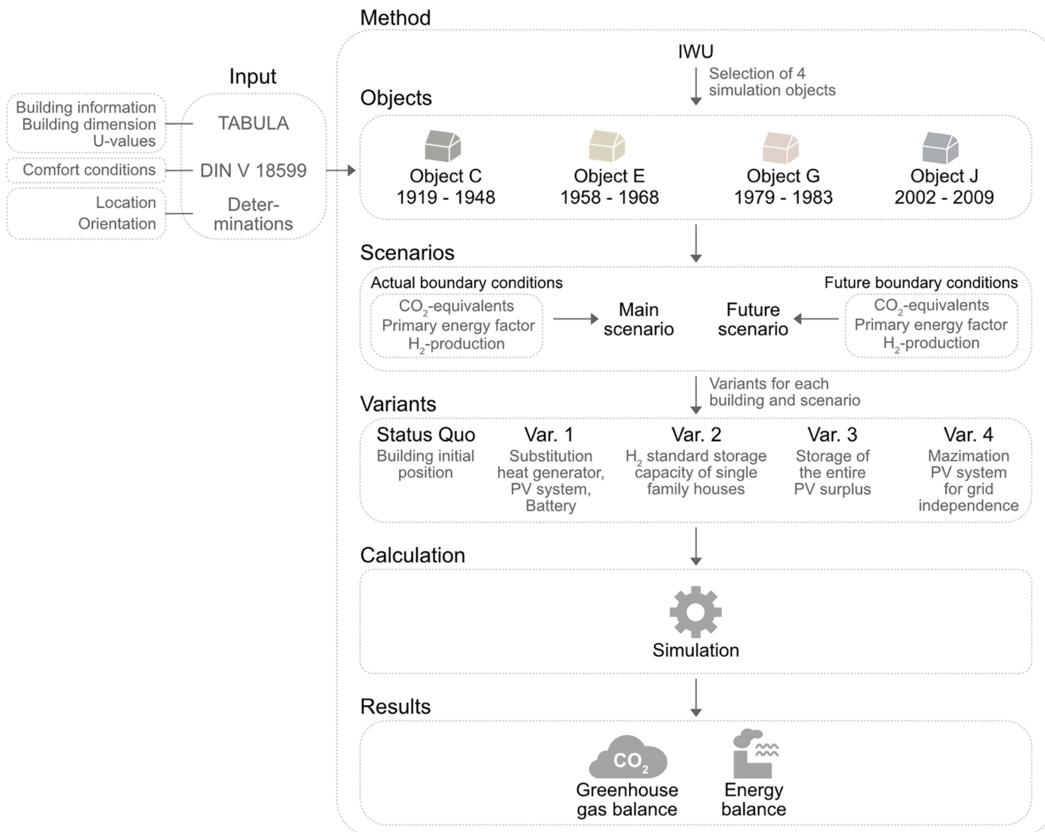

Fig. 1. Workflow summary.

The data from the specific reference objects were combined with defined assumptions, to enable a comparison between the objects and their transformation variants. Furthermore, this work examines a future scenario for developing measures, considering the progress of primary energy factors and greenhouse gas emissions as well as the efficiency increase of energy expenditure for energy storage in the form of hydrogen. The potential effects of various measures were identified and evaluated. Furthermore, space requirements for the selected actions were analyzed. The measures explicitly exclude direct interventions on the building envelope, to highlight the potential of implementing local energy production and storage.

The balancing is based on an auxiliary tool *EnerCalC* [21]. Due to the limitations of adding further components to the program, calculations were carried out independently. In this context, the results from the auxiliary program show slight deviations in the summation function and modifications were made regarding plausibility.

The base model includes a photovoltaic system, an air heat pump, a battery, an electrolyser, an energy storage system, and a fuel cell. The system pictogram in Fig. 2 shows the integration of the aforementioned base model. The system section illustrates the integration and processes categorized into electricity, heat, hydrogen storage, water, and oxygen within a building. The electricity demand is covered by drawing electricity directly and storing it in a battery [22,23]. With the addition of electrical energy, the electrolyser splits water into the chemical elements hydrogen and oxygen [7]. By using the renewable energy generated in the building, the process produces green hydrogen [24]. The long-term storage of the energy takes place outside the building envelope [25]. The fuel cell draws the stored hydrogen as required and converts it into thermal and electrical energy. The reaction product of combustion is water [7]. The thermal energy, or waste heat, is fed to the heat pump to increase the ambient temperature. The air heat pump draws electrical energy from the battery, fuel cell or public grid to extract thermal energy from the air in the environment and transfers it into the building, providing heat. The resulting heat is fed into a buffer and hot water storage tank which can supply the domestic hot water and heating energy demands [26].

2.1. Simulations

In 1990, the German Institute for Housing and Environment (*Deutsches Institut für Wohnen und Umwelt – IWU*) published the first edition of the building typology for residential buildings in Germany. The aim of the European project Typology Approach for Building Stock Energy Assessment (TABULA) between 2009 and 2012 was to develop a structure for the European building stock to create a standardized basis for calculating energy consumption and energy saving potentials. Based on various parameters, the project defines sample buildings as a reference for the specific building typologies and building age classes. These reflect the energy quality of the buildings by construction and age classes. The data sets are suitable to be used by energy modeling software. For the single-family house typology, TABULA refers to detached single and two-family houses. Significant characteristics for the classification into building age classes are historical censorship, legal frameworks, for example through new building regulations regarding thermal insulation, as well the results of statistical investigations. The classification of the number of detached and semi-detached houses and the total living space is based on the 2011 housing census [27]. The classification enables TABULA to obtain information on the average building physics parameters and the structure of referenced buildings. The database does not contain specific floor plans for the representative objects. The buildings listed in TABULA are not specified regionally [28].

Based on the information [27,29,30], the building age class with the highest average single-family house stock for the epoch was selected for comparison from the four epochs of the *Gründerzeit*, the post-war period, the oil crisis of the 1970's and the climate adaptation period, Fig. 3. For

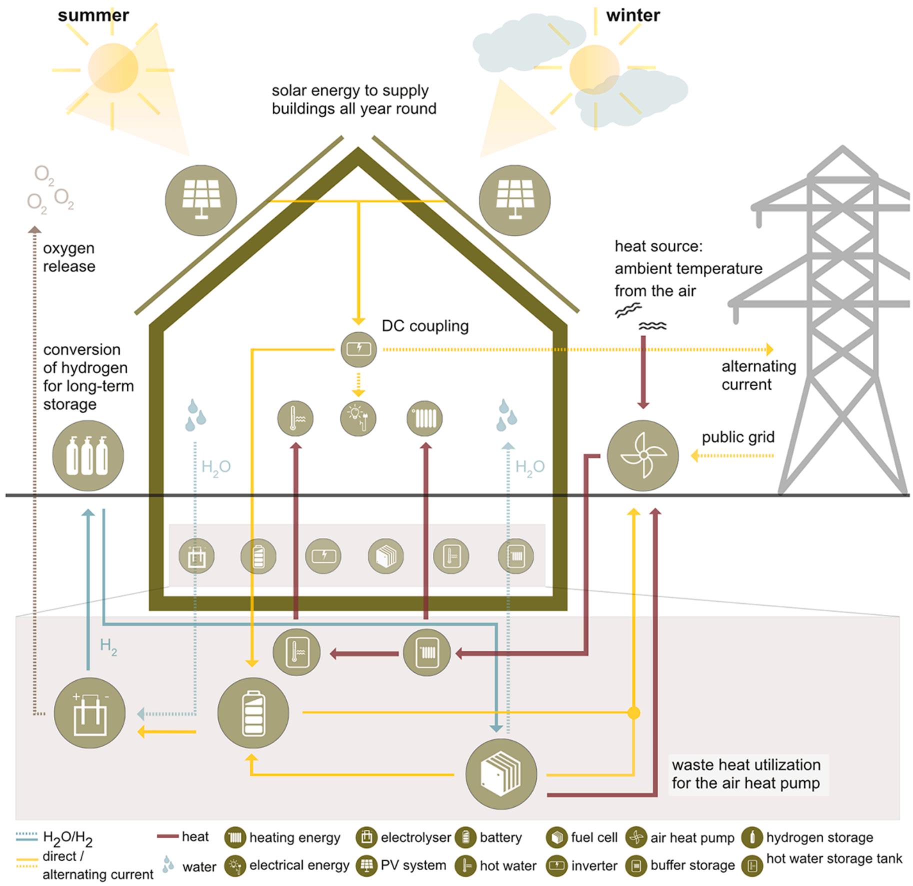

Fig. 2. System section with all the merged measures.

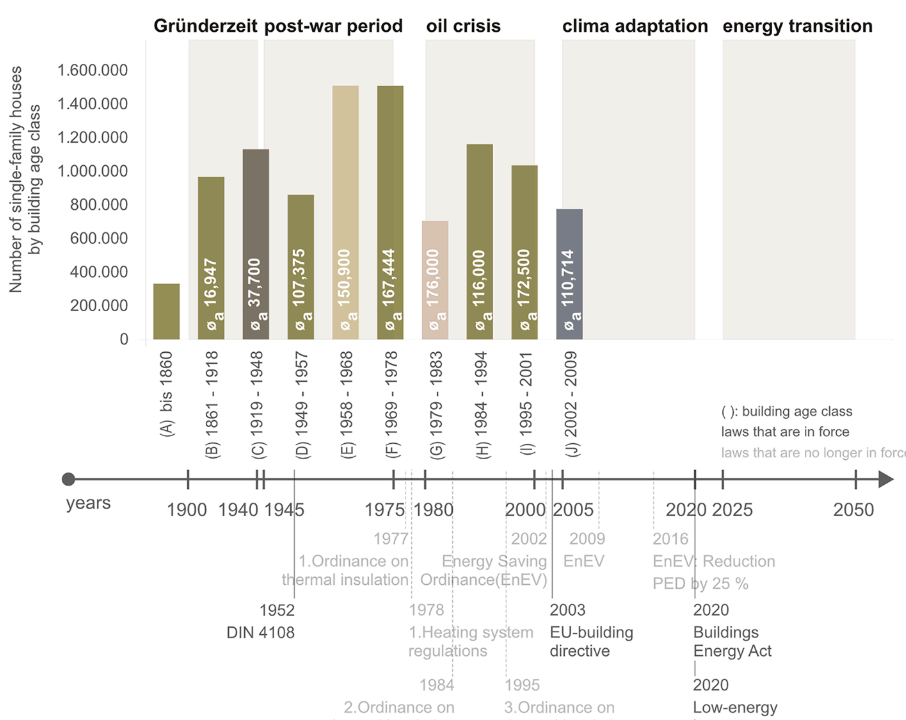

Fig. 3. Overview of building age classes according to [27,29,30].

the *Gründerzeit*, the building data from the construction period 1919 to 1948 was selected. The 1969 to 1978 building classification has a larger building stock than the 1958 to 1968 period. The building age class 1979 to 1983 determined by the IWU is used as the third object of comparison. The reference object for the annual period 2002 to 2009 is selected as a reference for the climate adaptation period. Their main constructive and typological characteristics are provided by TABULA and represent typical examples of the selected time period. The main differences between the buildings lie in the thermal building envelope. For example, building age class C is characterized by a wooden beam ceiling without insulation. This contrasts with building age class J that has a pitched roof with 16 cm thermal insulation. Further main characteristics and differences between the buildings can be taken from Table 1 according to [28,31] using U-values. To establish a comparison, four representative buildings were analyzed to highlight the effectiveness of decentralized energy production and storage and to which extent point net zero emissions can be achieved through the transformation.

EnerCalC provides support for energy and CO_2 balancing in accordance with the DIN V 18599 energy performance calculation ruleset for buildings [21]. According to the DIN V 18599–1 the lighting energy consumption is neglected in the energy balance of residential buildings [32]. The building location, its geometry and the roof orientation and inclination are fundamental to define the solar energy gains [22]. To create a best-case scenario, the buildings were aligned with the gable end facing north. This allows, after [22,23], for maximum PV system equipment. The specific building information and parameters were gathered from TABULA and DIN V 18599 [28,32]. Table 2 contains the model specifications assumed in *EnerCalC* that relate to the comfort conditions of the HVAC system. The assumptions were applied to the four buildings.

The information was used as input for the *EnerCalC* calculation and forms the results of the status quo and variant 1. The results from variant 1 are applied as the basis for the other scenarios for the subsequent calculation approach including energy storage through hydrogen production. The calculation is done with a monthly balance over one year. This enables the differentiation of energy surpluses from decentralized energy generation and energy requirements to cover the building heating supply due to seasonal fluctuations over the year.

To produce hydrogen via water electrolysis, a net requirement of 53kWh electricity input per kilogram H_2 output was assumed. The target for future hydrogen production is set around 40.4 kWh per kilogram hydrogen [8]. The calorific value of hydrogen of 33.3 kWh/kg and the heat and electric efficiency rates of 50 % are the basis for the calculation of the produced energy through the fuel cell [7,33].

The monthly balance shows that there is a surplus of electrical energy in the months of April to September. This provides the basis for the calculation approach for hydrogen production. A main grid consumption can be determined for the months January to March and October to December. For these months, a percentage distribution of the fuel cell use over the specific monthly heat demand is to be calculated. The use of thermal and electrical energy from the fuel cell follows the approach of providing the electrical energy for the heat pump and feeding the waste heat to the intake of the outdoor unit of an air heat pump. The aim is to increase the source temperature, resulting in an improved COP.

Therefore, it is assumed that 40 % of the waste heat is lost during transportation and the amount of heat, Q, is defined as 60 % of the waste heat. The heat capacity of the transfer medium air is 1.01 kJ/kg*K [34].

Table 1
Main characteristics of the selected building age classes as U-value [W/(m²K)].

Building age class	Floor	External Wall	Roof	Window
C	0.77	1.7	1.4	2.8
E	1.08	1.2	0.8	2.8
G	0.8	0.8	0.5	4.3
J	0.28	0.3	0.25	1.4

Table 2
EnerCalC model specifications Status Quo.

Comfort condition operation HVAC systems	Assumption
Air tightness	6.0 h^1
Thermal bridge factor	0.1 W/(m^{2}K)
Window ventilation	0.1 h^1
Sun protection	Not available
Cooling	Not available
Night ventilation	Yes
Ventilation control	Manually via window
Interior temperature	20 °C
Heat generator	Low-temperature boiler (J.: condensing boiler)
Transfer system	Radiator 55/45 °C
Room temperature control	P-Control
Domestic hot water preparation	Central without circulation

An efficient air flow of an air source heat pump is between 400 and 500 cubic feet per minute [35]. The standard definition of the density for the standard atmosphere at sea level and a temperature of 15 °C of the transfer medium air is p = 1.225 kg/m^3 [36]. To simplify subsequent steps, the mass flow rate is determined in kg/h. This results in a constant mass flow of 936.58 kg/h.

The new average monthly temperature due to waste heat utilization is calculated as follows:

$$\varnothing t_2 = \varnothing t_1 + \frac{\left(Q_{Ptherm.,out}\,[kWh]\cdot 0.6\cdot 3600\left[\frac{kJ}{kWh}\right]\div X_{days}\left[\frac{d}{M}\right]\div 24\left[\frac{h}{d}\right]\right)}{936.58\left[\frac{kg}{h}\right]\cdot 1.01\left[\frac{kJ}{kgK}\right]} \tag{1}$$

with:

$\varnothing t_2$: new average outdoor air temperature [°C].
$\varnothing t_1$: actual average outdoor air temperature [°C].
$Q_{Ptherm.,\,out}$: fuel cell heat [kWh].
X_{days}: Amount of days/month.

A simplified method of calculating the COP of a heat pump is given by a summarized formula (2) [37] and serves as the basis for the COP recalculation taking into account the increased input temperature, ⌀t2:

$$COP = 5.17 - 0.06 \bullet Tflow + 0.09 \bullet Toutdoor \tag{2}$$

The recalculated COP determines the specific final energy demand for the scenarios. Another constant assumption for the scenarios is the requirements for battery charging and its losses in variant 1. In the virtual scenario, the amount of the stored hydrogen is extrapolated to reach the building's autarchy from the grid. This requires an electricity production

Table 3
Primary Energy factors and Carbon Emissions according to sources [32,38–40].

Energy source	Primary Energy Factor f_p of the non-renewable share		Carbon Emissions X_{CO2} g/kWh	
	Main Scenario	Future Scenario	Main Scenario	Future Scenario
Natural gas	1.1*	1.07***	240*	228***
Electricity (from network)	1.8*	0.78****	550*	259****
Electricity (renewable own production)	0*	0	0*	0
Green hydrogen	0.06**	0.05**/***	21**	18**/***
Displacement electricity mix for PV (final energy from balance limit)	1.8*	0.78****	550*	259****

*: [32], Attachment A.
**: [38], p. 19.
***: [39], p. 9, 15.
****: [40], p. 7.

to constantly drive the electrolysis. The variant neglects an increase in PV area. The factors for primary energy demand and greenhouse gas emissions have been selected according to the specific energy sources [32]. Currently, the DIN V 18599 does not provide any information on the primary energy factor of hydrogen. Table 3 summarizes the primary energy factors and CO_2 equivalents relevant for this work.

Excess renewable energy that is fed into the public grid is credited to the building in the balance, however, double balancing of the renewable share must be excluded [41]. The primary energy factor and emitted CO_2 emissions of green hydrogen are determined for the entire life cycle. Considering that the electricity for hydrogen production comes from renewable sources, a primary energy factor of 0.0 and greenhouse gas emissions of 0.0 gCO_2 eq./kWh are set according to with DIN V 18599–1 [32]. The aim is to store the surplus electricity without considering this amount as a credit. The electricity generated by the fuel cell is deducted from the primary energy demand and the greenhouse gas emissions with the factor of the electricity purchase.

Furthermore, the system integration of hydrogen is considered in relation to the architecture. The information of the *picea* plant serves as the basis [42]. This system consists of an indoor and outdoor unit. The indoor unit includes the electrolyser, a battery and water treatment system, while the outdoor unit includes the compact compressor and the gas cylinders for long-term storage. The standard system of a detached or semi-detached house generates a maximum of 1,500 kWh of electrical energy from the chemically stored energy. The space requirement for the indoor unit is 1.5 m^2 and for the outdoor unit 6 m^2. Both values refer to the standard configuration of a single-family house in which a maximum of 1,500 kWh of hydrogen is stored in 5 gas cylinder packs. Additional space is required for the movement area [9]. The acquisition costs of the entire hydrogen system (excluding PV system and annual service fee) for storing 1,500 kWh electrical energy amount to 160,000 € (Valued Added Tax is waived) [42].

2.2. Variants

The present study developed several variants to examine the step-by-step implementation of the different measures under the premise of local energy generation and storage. The variants consider two factors. First, the buildings are differentiated in terms of retrofitting measures due to the economic challenge caused by the low implementation of the previously described refurbishment distribution. Then, it considers replacing system technology. Second, it considers the significance and effects of the transformation. Therefore, a main and a future scenario of the respective variant is carried out. The differences between the future and the main scenario lie in the assumption that the primary energy factors and greenhouse gas emissions will change, and that process for hydrogen production will become more efficient.

For each of the four reference objects, four variants were simulated for both scenarios, starting from the status quo. Fig. 4 summarizes the measures of each variant, which are described in more detail below. At the end of this chapter, Table 4 represents an overview about the variants.

2.2.1. Status quo

The status quo forms the starting point for the following variants and the main comparison of the impacts. The buildings in the status quo are in their original state with their building age class-specific features and the original heat supply.

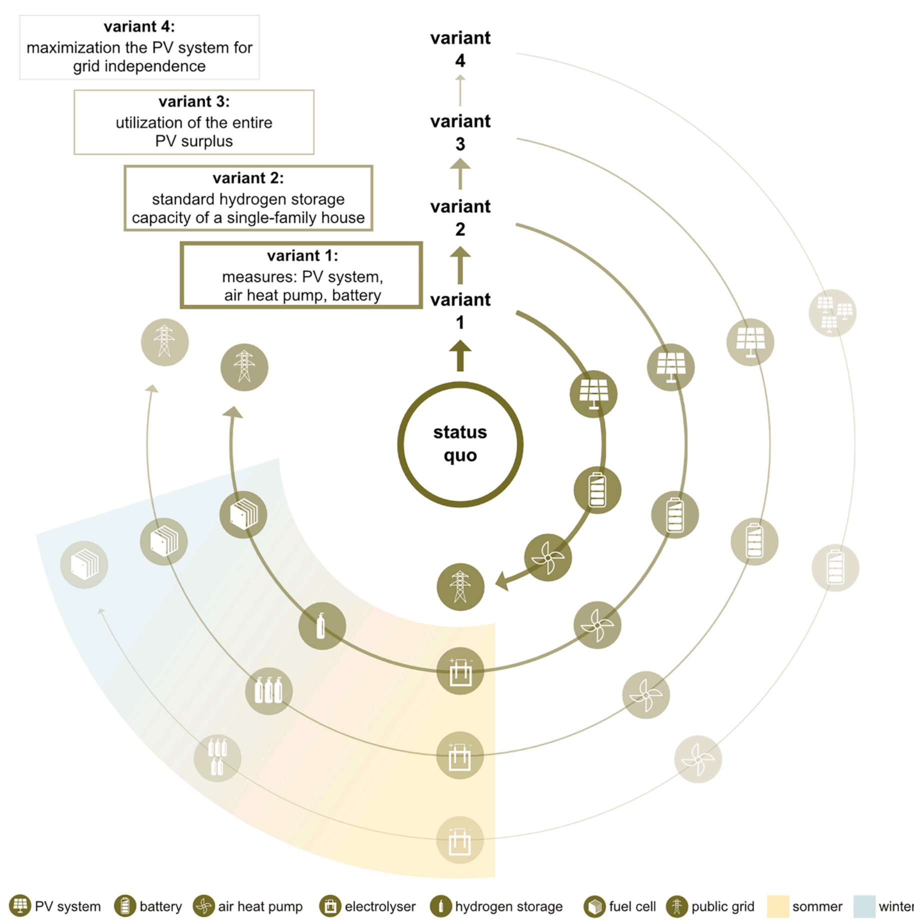

Fig. 4. Variants.

Table 4
Comparison of the variants.

Indicators	Main heat generator	PV system	Battery	Electrolyser	H_2-storage	Fuel cell	Public grid
Status Quo	Condensing boiler	–	–	–	–	–	Essentials
Variant 1	Heat pump	Aligned with reference	Yes	–	–	–	Yes
Variant 2	Heat pump	Aligned with reference	Yes	Yes	Standard storage system	Yes	Yes
Variant 3	Heat pump	Aligned with reference	Yes	Yes	Entire PV surplus	Yes	Yes
Variant 4	Heat pump	Maximize PV system for independence	Yes	Yes	Entire PV surplus	Yes	No

2.2.2. Variant 1

In variant 1, buildings are retrofitted with improved through local energy generation and storage: the buildings are equipped with a maximized PV system and batteries to store the generated energy. To use the electrical energy for heating requirements, the buildings are equipped with an air heat pump which replaces the existing heat generation.

2.2.3. Variant 2

In addition to the elements implemented in variant 1, the second variant includes the integration of hydrogen as season-independent decentralized energy storage. The prerequisites for hydrogen integration are hydrogen production by electrolysis, its storage in gas cylinders and a fuel cell for energy recovery, which are integrated into the building as additional elements. The electrolyser converts the surplus electricity into hydrogen. The scenario is designed for the standard storage capacity of a detached house. The hydrogen is stored in tanks and converted into thermal and electrical energy through fuel cells when it is required. In this scenario, the main task is to what extent the storage capacity of the hydrogen tanks is sufficient to fully cover the energy demand of the building. In case of an excess demand, energy is drawn from the grid. If the electricity production from the PV system is higher than the energy needed for hydrogen production, electric energy is fed into the grid.

2.2.4. Variant 3

Variant 3 examines the maximum amount of energy stored as hydrogen generated from the entire PV surplus. As in variant 2, the building is equipped with a PV system, an air heat pump, an electrical storage, an electrolyser, a hydrogen storage and a fuel cell. The variant considers the question of how much energy is recovered from the stored hydrogen from the PV surplus minus the direct electricity offset and battery storage with extended storage capacity, and whether this amount is sufficient to cover the building's demands. In this variant, quantifying the amount of energy is crucial, weather the storage capacity exceeds the demand or whether it is necessary to draw electricity from the grid.

2.2.5. Variant 4

Variant 4, the virtual variant, aims to determine the amount of energy storage required to minimize energy demand and to achieve complete grid independence for the selected building age classes. This variant examines the amount of electricity supplied from locally generated renewable energies to store it as hydrogen and make it available to the buildings in demand-oriented months.

3. Results

The results are based on the usable energy demand of the four investigated objects, the electricity balances of variants 1 to 4 for a selected object and an energy flow diagram. In addition, the primary energy demand and greenhouse gas emissions of the main scenario as well as the operating costs and space requirements have been considered. This is followed by an extrapolation to the entire building stock in Germany of four building age classes and a derivation of the hypotheses. Finally, the difference in total greenhouse gas emissions in the future scenario is discussed.

3.1. Main scenario: Status quo to variant 4

Overall, the usable energy demand of the four selected reference objects is decreasing, as shown in Table 5. This is primarily due to the further enhancement of the thermal building envelope performance through improved U-values. The exception is the usable energy demand of the building from construction age class E. Due to a deterioration in the floor U-value, the usable energy demand increases in comparison to the reference object in building age class C.

The different system configurations resulted in a varying electricity balance for the buildings under consideration. Fig. 5 shows an example of the distribution of electricity sources for providing the useful energy demand for heating and hot water for variants 1 to 4, including the categories PV and batteries, grid supply, electrical energy from the fuel cell and the grid feed-in for the reference building of age class G. This representation can be transferred to the other properties examined, whereby only the absolute values differ. The results clearly show the shift in decentralized energy production in contrast to building energy consumption. A key finding is the seasonal shift in energy use, which is made possible by long-term storage. This means that locally generated electricity can be stored and accessed in the months when demand is higher. The introduction of hydrogen as an energy storage system significantly reduces grid feed-in between April and September. In addition, the combination of energy recovery by fuel cells and the use of the waste heat generated in an air heat pump leads to a lower final energy demand, especially in the months of September to April. In variant 2, which uses the standard storage capacity, the COP of the heat pump improves by around 7 % compared to variant 1. In variant 3, the improvement is 8 % to 9 % compared to variant 1.

Variant 4, which focuses on grid independence, is achieved by maximizing the system. However, the increased amount of electrical energy generated by the recovery of hydrogen via the fuel cell reveals inefficiencies. This leads to the conclusion that complete grid independence is unrealistic for older building due to the high energy demand and the resulting increased space requirements for PV modules and system.

The exemplary comparison of the total energy balance from the status quo to variant 4 for the reference object of building age class G, Fig. 6, depicts the change in the energy shares including losses due to the different system configurations. The consideration of variants 1 to 3 illustrates the change in decentralized long-term storage. This is shown by the increasing grid consumption, the decreasing PV credit and the increasing energy recovery with growing losses. On the one hand, the graphic shows that local storage using hydrogen plays a subordinate role due to the increase in grid consumption in variants 1 to 3 from 27.0 kWh/(m^2a) to 38.4 kWh/(m^2a). On the other hand, long-term storage reduces the building's final energy demand and maximizes energy self-

Table 5
Usable annual energy demand for heating and hot water in [kWh/m^2]. Based on results from *EnerCalC* ("«EnerCalC», 2023").

Building age class	Usable energy demand [kWh/(m^2a)]
C	302.6
E	397.9
G	199.3
J	141.7

Fig. 5. Electricity balance for variants one to four of the reference building of building age class G. Based on results from *EnerCalC* ("«EnerCalC», 2023").

consumption.

An exemplary illustration of the energy flows of the object of building age class G, variant 2, is depicted in Fig. 7. The graphic divides the electrical and thermal energy flows to cover the specific use energy demand. Various implications within the building can be observed: on one hand, the locally generated solar energy used for energy conversion and hydrogen storage, the battery energy storage, and the directly accountable electrical energy. On the other hand, the thermal energy obtained by recovering the locally stored energy, as well as the additional electrical energy from the grid to meet the building's demand. Furthermore, the losses through the conversion processes are evident.

The energy flow diagram depicts the decentralized energy storage via hydrogen. To show how the hydrogen storage system is used, Fig. 8 shows the storage's monthly charging and discharging for the reference building of class G, variant 2. The configuration provides 1,500 kWh electrical energy through storage. The positive values for the months of April to September represent the charging through the surplus of decentral generated electrical energy and the negative value indicates the discharging in the months October to March for energy recovery. For storage capacity, the values must be cumulated or accumulated. The figure shows that the cold months of January and December have the highest energy recovery requirements. The highest storage is in the summer months June and July.

The analysis, in Fig. 9, shows significant reductions in primary energy demand and greenhouse gas emissions across the building age classes when shifting from fossil fuel-based systems to those incorporating renewable energy and storage technologies. For newer buildings, which follow more recent insulation standards, there is a marked improvement in energy demand, except for age class E. In variant 1, the integration of a PV system, a battery storage, and an air heat pump results in a 60–66 % reduction in energy consumption and emissions compared to the baseline. Further reductions are possible with decentralized hydrogen storage, which utilizes waste heat from fuel cells.

Variants 1 to 3 show overall reductions in primary energy use and emissions between 60–89 %, with waste heat from local energy storage improving the heat pump's COP, leading to lower energy requirements. However, the use of hydrogen introduces efficiency losses, which impacts the grid feed-in credits and slightly raises the actual primary energy demand in some cases. Variants 2 and 3 see a rise in net emissions compared to variant 1 due to the substitution credit methodology, which includes lower feed-in credits.

While hydrogen storage enables greater grid independence, the limited storage capacity in some variants prevents full energy self-sufficiency, leading to surplus energy production in certain scenarios. This surplus energy is fed back into the grid, but overcompensation due to excess energy production results in negative primary energy demand and CO_2 emissions in some cases. Despite this, the credit losses and inefficiencies from hydrogen mean that it may not always contribute effectively to decarbonization.

3.2. Main scenario: Operating cost and space requirement for long-term storage

The analysis of operating cost development, Fig. 10, entails the direct consumption of individual variants considering gas prices, electricity prices [43], as well as feed-in tariffs [44]. The trend indicates that a reduction in overall costs can be achieved through the substitution of the heat generator, despite the increased individual prices per kWh [43], owing to the improved final energy demand. Hydrogen energy storage further reduces annual consumption costs despite lower feed-in tariffs. Additionally, the life cycle costs, for example equipment replacement, acquisition costs of PV system, heat pump, hydrogen integration and the maintenance expenses and service life, must be considered for an economic building [45]. In this case the costs for the facility and additional components were deliberately excluded.

In variants 2 to 4, the use of decentralized energy storage via hydrogen leads to an increased space requirement for the energy systems in the investigated building age classes C, E, G and J, Fig. 11, according

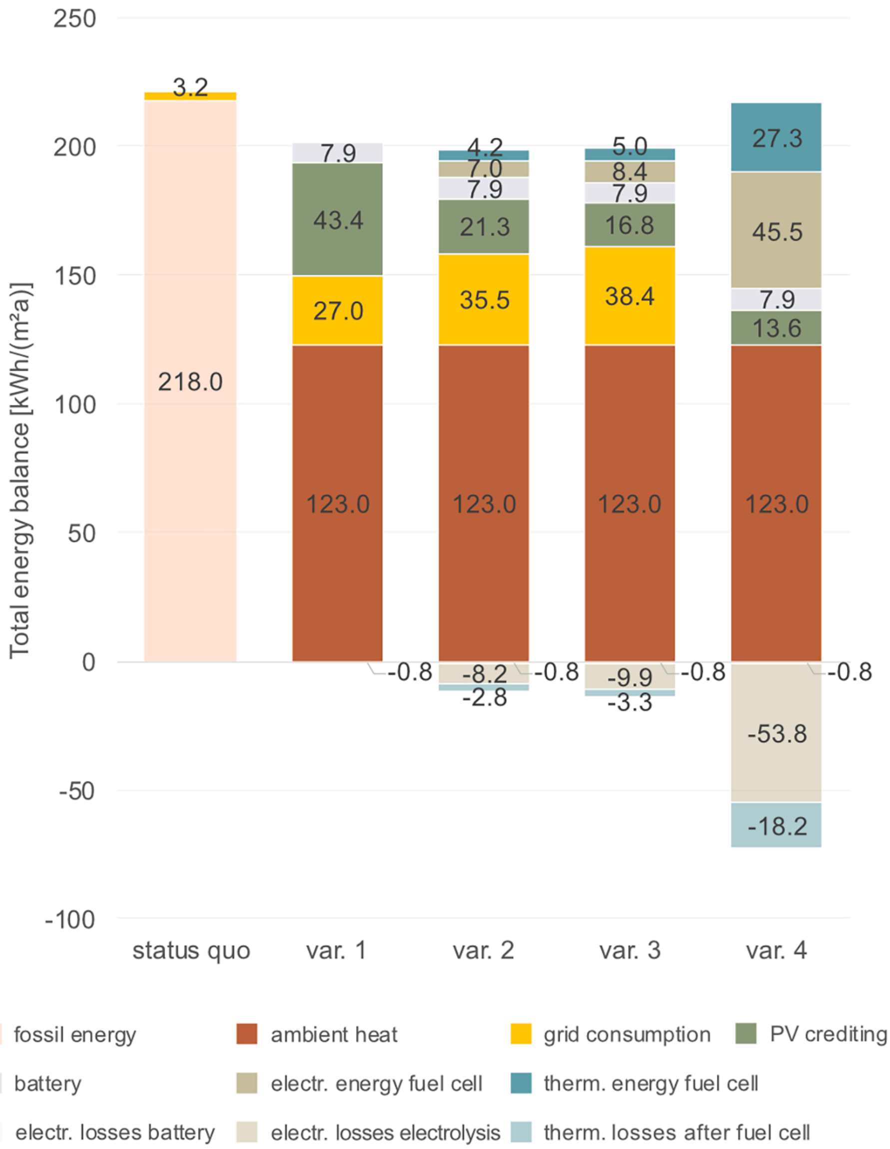

Fig. 6. Comparison of the change in the total energy balance of the reference building of building age class G, status quo to variant 4. Based on results from *EnerCalC* ("«EnerCalC», 2023").

to the space requirements [9]. In variant 2, the space requirement for the indoor unit is 1.5 m^2 and for the outdoor unit 6 m^2, excluding the necessary movement areas for repair and maintenance purposes. With long-term storage of the entire PV surplus, variant 3, the space requirements increase by a factor of two to three. Variant 4 shows that the space required indoors and outdoors for long-term storage decreases with increasing building age class if the entire energy supply is provided by decentralized storage. This is illustrated by comparison between building age classes C and J. While at least 21 m^2 are required for the indoor unit and 84 m^2 for the outdoor unit for the reference property in building age class C, at least 4.5 m^2 indoors and 18 m^2 outdoors are sufficient for the class J property. The differences show the effect of an improved building envelope on building performance in terms of decentralized energy generation and storage.

The investment costs increase in proportion to the number of systems by around 160,000 € [42].

3.3. Main scenario: Extrapolation of the entire building stock

The extrapolation of the results to the entire building stock considers an approximation of the change in emitted CO_2 emissions when converting the building stock to the examined variants. In the approximation, different locations, orientation and window-to-wall ratios are not considered. Fig. 12 is based on a total of 4,119,000 single-family houses of the construction age classes from the periods 1919 to 1948, 1958 to 1968, 1979 to 1983 and 2002 to 2009 with different thermal building envelope properties [27]. The graph shows the development of total greenhouse gas emissions of the main scenario for the examined variants. The four building age classes emit around 45,825,600 tons of carbon dioxide per year, if the buildings have not undergone any retrofitting measures and are subject to the same boundary conditions. Implementing a PV system, a battery and an air heat pump, reduces greenhouse gas emissions by around 89 % compared to the status quo. Local energy storage using hydrogen with standard storage capacity reduces greenhouse gas emissions by around 81 % compared to the original building stock. The increase in carbon dioxide emissions from variant 1 to variant 2 can be attributed to a decrease of the credits, which results from reduced electricity feed-in into the public grid. Nevertheless, if credits are excluded, variant 2 exhibits lower direct carbon emissions in comparison to variant 1. Overall, the building, in variant 4, is locally supplied with energy from renewable sources resulting in a primary energy demand and greenhouse gas emissions of 0.0 kWh/m^2

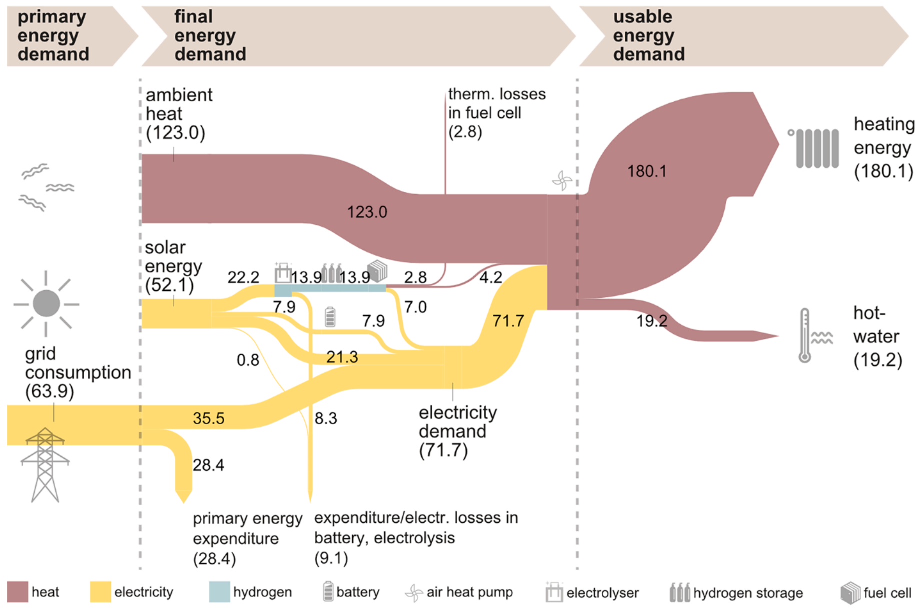

Fig. 7. Energy flow diagram of the reference property (building age class G, variant 2). Based on results from *EnerCalC* ("«EnerCalC», 2023").

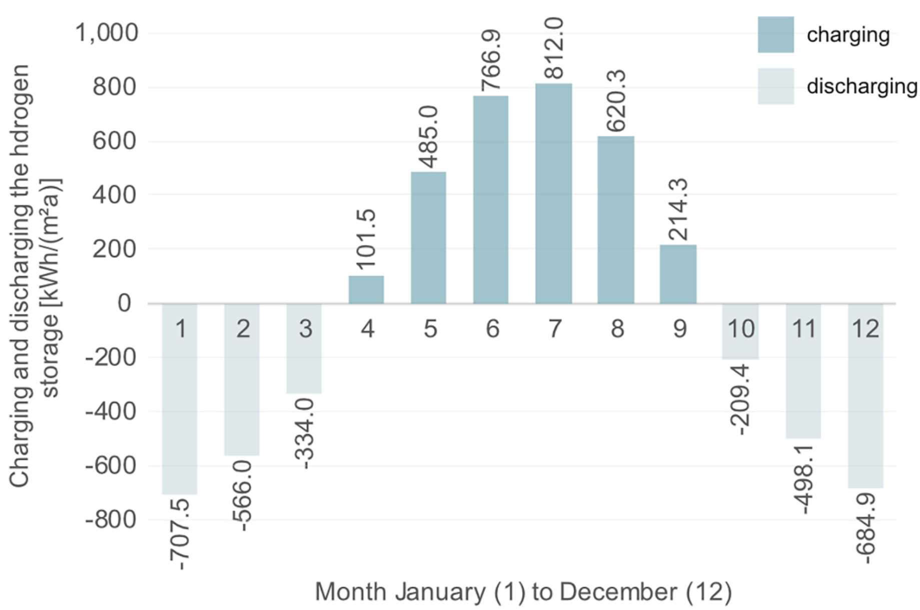

Fig. 8. Monthly charging and discharging the hydrogen storage (building age class G, variant 2).

and 0.0 kgCO_2-eq./m^2 per year. There is no overcompensation due to the needs-based adaptation of energy generation. The use of the stored medium in a fuel cell enables a limited increase in the COP of the heat pump using waste heat. The additional amount of energy generated by PV and the space requirements for the hydrogen production, the local storage medium and energy recovery, question the real possibility of implementing this scenario due to spatial restrictions in the single-family house category. As buildings get older, it is conceivable that the system could be maximized, and energy recovery equipment installed on the building sites.

3.4. Future scenario

By further developing the production process for energy storage and reducing conversion losses, Fig. 13, variant 2 of the future scenarios achieves a higher grid feed-in compared to the main scenario while maintaining the same level of hydrogen storage. The energy storage shows that variant 3 achieves a higher energy storage capacity and the conversion losses are close to zero. Overall, the scenario provides an outlook on the transformation of the energy mix and the further development of research with the aim of accelerating decarbonization. Increasing the efficiency of energy conversion for storing electricity reduces the area of the needed PV systems. The space requirements for technical equipment and storage remain unchanged.

4. Limitations

Extensive information and studies are available on the topic of hydrogen as an energy storage medium. Difficulties and challenges in the work were caused by the provision of information on the calculation methods for the integration of hydrogen into the technical building system. In this context, the work does not deal with the use of waste heat

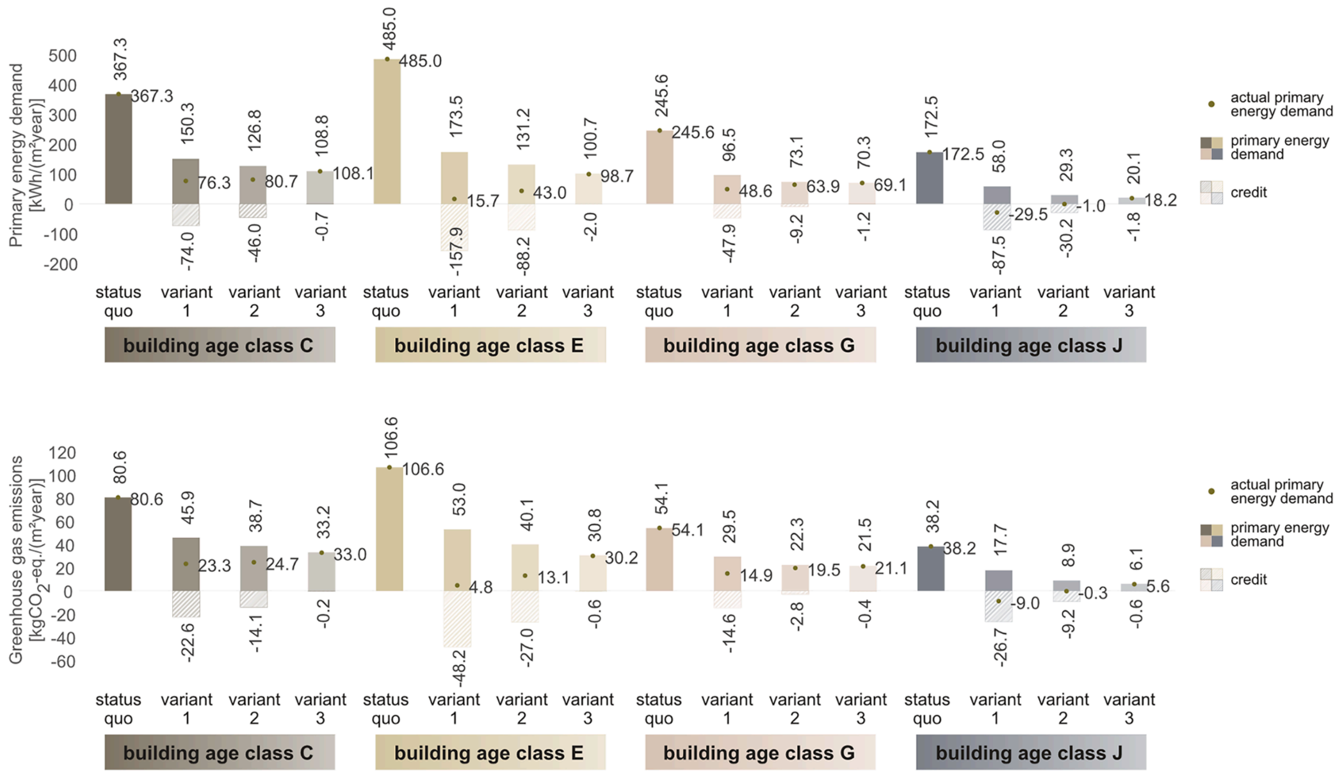

Fig. 9. Primary energy requirements and greenhouse gas emissions of building age classes C, E, G and J. Based on results from *EnerCalC* ("«EnerCalC», 2023").

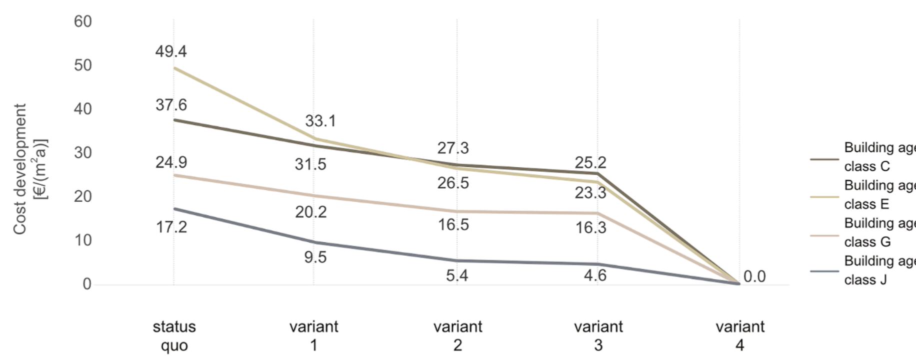

Fig. 10. Cost development regarding gas and electricity prices as well as feed-in tariffs.

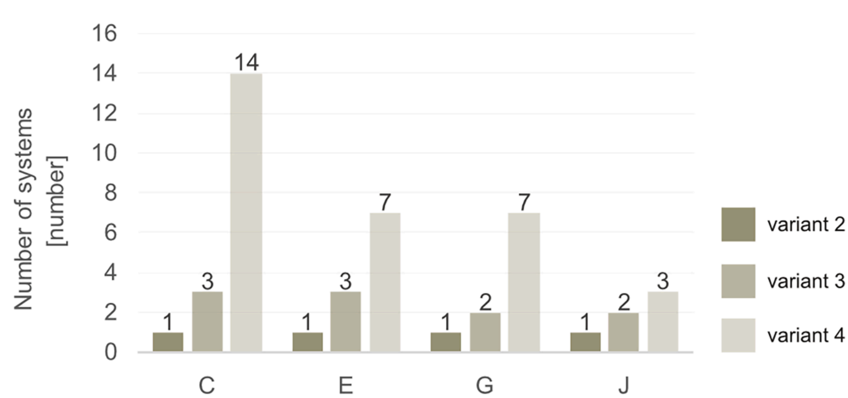

Fig. 11. Number of systems for long-term storage of building age classes C, E, G and J.

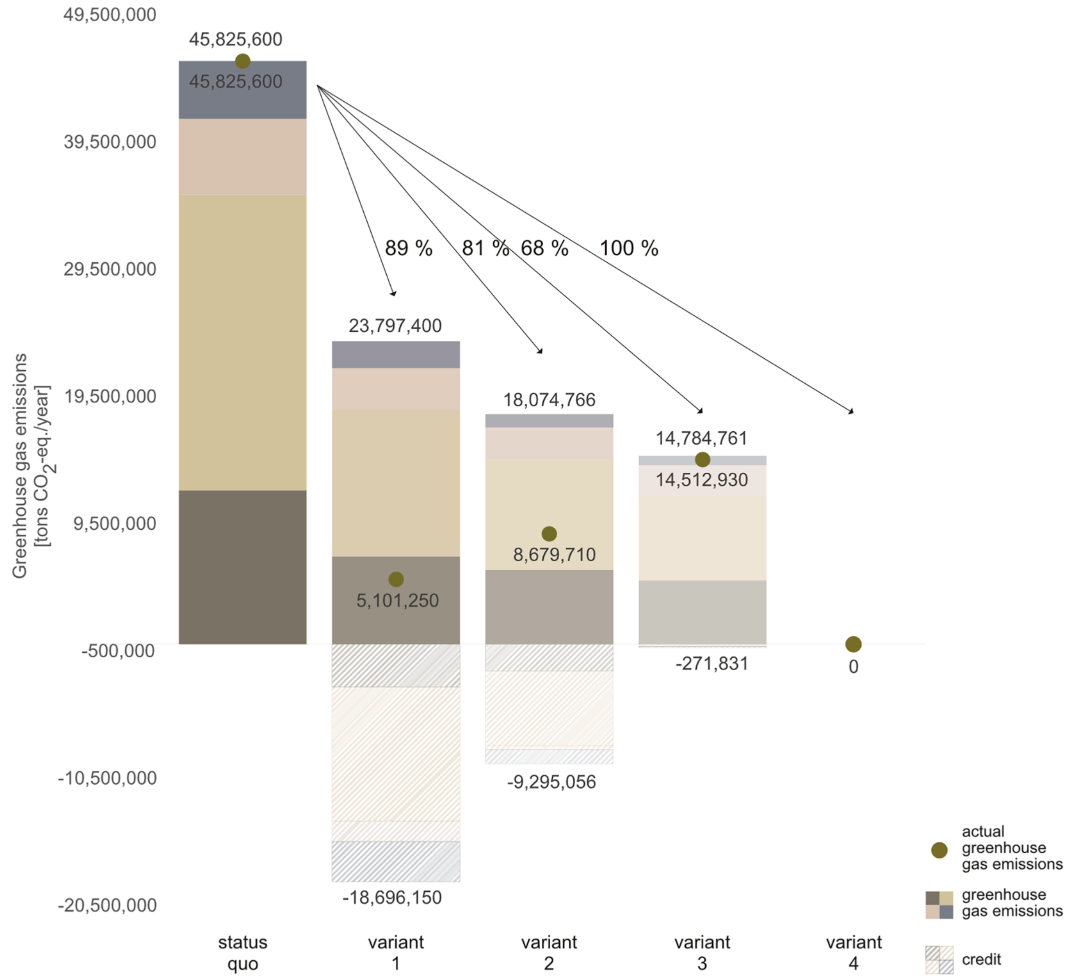

Fig. 12. Development of total greenhouse gas emissions of the building age classes C, E, G and J. Based on results from *EnerCalC* ("«EnerCalC», 2023").

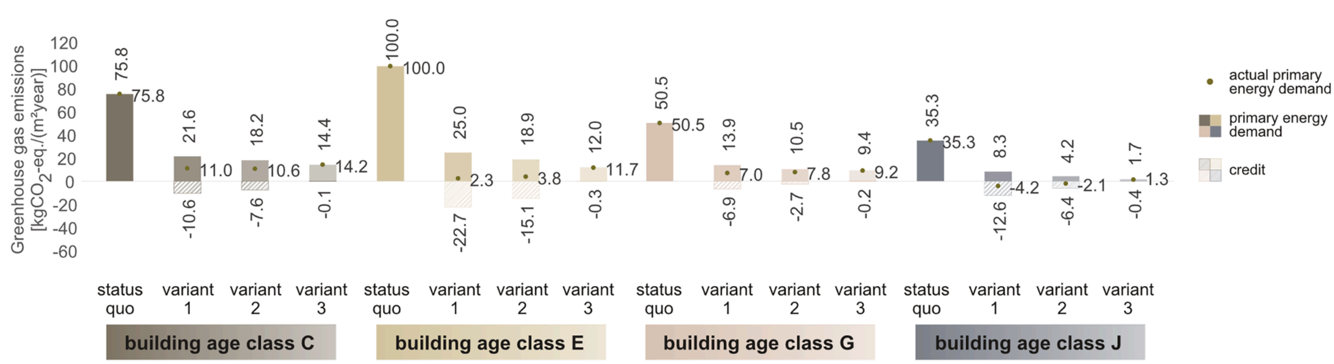

Fig. 13. Greenhouse gas emissions of building age classes C, E, G and J for the future scenario. Based on results from *EnerCalC* ("«EnerCalC», 2023").

from electrolysis in a hot water storage tank and the resulting effects on energy requirements and emissions. In addition, the standard design of the connection of thermal energy from the fuel cell with the buffer or hot water storage tank is not addressed. Furthermore, the calculation approach of the virtual scenario assumes that, with increasing electricity production, the direct electricity billing through the purchase and battery storage is adjusted to the final energy demand of the buildings. In this context, it should be noted that there is a possibility of direct electricity billing as the number of modules increases, particularly in the winter months. The assumption would lead to a lower electricity demand in the months with increased electricity billing and would have an impact on the actual amount of electricity to be produced locally and the storage requirements.

The investigation on the potential of local energy production and storage in single-family houses requires further development through a feasibility study to test a practical application. The results lead to the question of the economic viability and financing options for the user, as well as the cost amortization. In this context, it is worth investigating the added value of combining active measures with passive refurbishment measures, such as retrofitting.

5. Discussion of the results

Most single-family houses, around 9,383,000, were built before 2002 when the Energy Saving Ordinance (Energieeinsparverordnung) was introduced, which means that the buildings have a low performance thermal insulation [27].

The advantages of energy storage are a reduction in grid dependency and grid overload. The virtual variant based on the design of a climate-neutral building stock shows that implementation is not feasible due to the high space requirements indoors and outdoors for the integration of renewable energies for hydrogen production, as well as the components related to the energy storage and recovery. The installation of local energy sources, for example a PV system, has a significant impact on greenhouse gas emissions. The environmental impact is minimized by self-used electrical energy. In newer buildings, the self-consumption of electricity and its injection into the public grid results in negative greenhouse gas emissions due to the high allocation of credits.

Overall, the results show that local energy generation and storage can be implemented for the single-family house typology. Replacing the heat generation and the main energy source reduces greenhouse gas emissions and energy demands significantly. Retrofit measures as increased thermal insulation and new windows reduce the usefulenergy requirement. However, the measures do not enable the full decarbonization of the typology. Decarbonization is achieved by combining decentralized energy generation and storage. Hydrogen as an investigated solution enables energy storage and contributes to the decarbonization of the building sector, but its application as an energy storage in single-family houses is questionable due to the high costs and significant space requirements.

Through a specifically maximized PV system tailored to the analyzed buildings, the four investigated buildings receive a specific PV yield. It is demonstrated that, despite the standard configuration of hydrogen storage specified for single-family houses, grid feeding remains essential for space-saving operation. Furthermore, nearly 50 % is attributed to the energy storage and recovery losses, highlighting the inefficiency of the process in terms of the provided energy. Hydrogen offers an added value as an energy storage system in more recent building age classes, where the useful energy requirements are comparatively low. Overall, decentralized energy storage is important for the goal of maximum energy self-consumption and self-sufficiency of the building. The reduction in final energy demand due to long-term storage and energy recovery offers added value for decarbonization if the credit method is not considered.

In the future, energy storage using hydrogen has the potential to be an innovative and sustainable solution, specially, if efficiency rates for hydrogen production and use are furtherly improved. The change in climatic conditions must be considered and differentiated for more specific forecasts.

6. Conclusion

The implementation of retrofit measures is essential to achieve climate neutrality by 2045. The implementation of these measures is associated with high costs and limited funding opportunities to cover them. Achieving the target depends on the owner's income and their interest in investing in refurbishment measures, in combination with existing funding opportunities. A decisive role for the decarbonization of the single-family house typology lies in the rapid implementation of refurbishment measures. Besides this, the study highlights the interdependencies between energy demand reduction, carbon emissions and current regulations and policies in Germany. For instance, referring to the analysis, variant 1 has the lowest carbon emissions due to the credit allocation method. However, this result is balanced on the yearly energy demand versus production and does not consider seasonal fluctuations and the resulting need for energy storage.

Variant 4, the net zero carbon variant, requires PV surface and storage capacities that are often difficult, if not impossible, to implement.

In future, due to the increasing renewable energy production in the electricity mix, the primary energy demand, and the subsequent CO_2 emissions, will decrease according to the primary energy factor. The decarbonization of the single-family house building stock can be only achieved increasing the renewable energy proportion and, in parallel, through a process that includes energy retrofit of buildings and the electricity grid expansion, combined with local storage.

CRediT authorship contribution statement

Lina Dworatzek: Writing – original draft, Visualization, Software, Investigation, Conceptualization. **Daniele Santucci:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Christoph van Treeck:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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