Energy Reports 16 (2026) 109619

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Impact of bundling and sequencing of measures in retrofit roadmaps with hybrid heat pump systems – A case study for a municipal non-residential building in Germany

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ARTICLE INFO

Keywords:
Non-residential buildings
Retrofit
Hybrid heat pump system
Ventilation system with heat recovery

ABSTRACT

Achieving climate neutrality in the building sector necessitates a well-balanced mix, entailing measures that reduce the space heating demand and measures to decarbonize the heat supply system. In non-residential buildings, the space heating demand can be reduced through both renovation measures targeting the building envelope and heat recovery from the ventilation system. In order to avoid CO_2 emissions, the implementation of the entire set of retrofit measures should be aimed at, but is often not practically feasible due to financial and other constraints. This issue may be addressed with a hybrid heat pump system, wherein the existing, fossil-fueled boiler continues to be operated to cover the residual thermal load until other retrofit measures have reduced the space heating demand to a level that it can only be covered by the heat pump. The proposed approach combines a techno-economic assessment of retrofit measures with a detailed simulation of the hybrid heat pump system across different stages of implemented retrofit measures. The process of bundling and sequencing gives rise to a multitude of combinatorial permutations of possible retrofit roadmaps. To apply the methodology to a real building as a case study, realistic requirements and constraints are transferred into filters to obtain a manageable number of possible roadmaps as a basis for exemplary roadmaps as scenarios. Hence, this approach is suitable for a techno-economic assessment of adequate measure bundles that ensure the transformation to carbon-neutral buildings despite limited resources.

1. Introduction

To mitigate the effects of climate change, climate goals have been set at various institutional levels. In recent years, these targets have become increasingly ambitious, with the target year being moved forward, whereby it turns out that the lower the institutional level, the more ambitious the climate targets become. While the European Union's target year for climate neutrality is 2050, Germany's is 2045, and Baden-Württemberg's, a federal state of Germany, is 2040. As buildings account for approximately 36% of the CO_2 emissions within the European Union, the building sector plays a pivotal role in achieving the European Union's climate goals (European Parliament, 2024). Consequently, the need for action to implement appropriate retrofit measures is constantly growing.

1.1. Definition of terms and focus

The set of measures to obtain a building that is carbon neutral in its utilization phase can be divided into two categories of measures with different purposes: reducing energy consumption and decarbonizing the energy supply. Retrofit measures are defined to subsume both types of measures. A retrofit roadmap is the result of scheduling (bundling and sequencing) these measures. This paper focuses on the space heating supply, while neglecting the domestic hot water supply and excluding building automation and other electric appliances, with the exception of a heat pump. The claim of the paper is to consider the critical technical measures that influence space heating. Therefore, the aforementioned two categories of measures can be specified as follows: measures to reduce the space heating demand by enhancing the building's energy efficiency and measures to decarbonize the heat supply for space heating by changing the heating system and the energy carrier.

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https://doi.org/10.1016/j.egyr.2026.109619
Received 2 December 2025; Received in revised form 16 May 2026; Accepted 13 August 2026
Available online 10 September 2026
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Nomenclature

Variables and parameters

AF	annuity factor [-]
E	energy [kWh]
f	(emission) factor [$\frac{g_{CO_2}}{kWh}$]
LCCH	levelized cost of changing heating system [$\frac{ct_€}{kWh}$]
LCSE	levelized cost of saved energy [$\frac{ct_€}{kWh}$]
N / n	number of … [-]
p	price [$\frac{€}{kWh}$]
q	specific space heating demand [$\frac{kWh}{m^2}$]
SFP	specific fan power [$\frac{Wh}{m^3}$]
SPF	seasonal performance factor [-]
T	lifetime (of a retrofit measure) [a]
X	Boolean variable if the retrofit measure is implemented [-]
ζ	utilization ratio of heat pump plus TES (>1) [-]
η	utilization ratio of existing boiler (<1) [-]
ϑ	temperature [°C]
ξ	degree of utilization of heat gains [-]

Subscripts and abbreviations

0	reference / standard state
CHP	combined heat and power
comb	combinations
COP	coefficient of performance
distr	distribution
EB	existing boiler
EC	energy carrier
el	electrical / electricity
emis	emission
EPBD	Energy Performance of Buildings Directive
ETS	Emission Trading System
HP	heat pump
HVAC	heating, ventilation and air conditioning
LC(C)A	life cycle (costing) analysis
MILP	mixed integer linear programming
NSGA	non-dominated sorting genetic algorithm
nZEB	nearly Zero Energy Building
O&M	operation and maintenance
perm	permutations
PV	photovoltaic
SH	space heating
TES	thermal energy storage
th	thermal

Heating systems that consist of a combination of two heating systems of different technologies are commonly called hybrid heating systems. In general, a hybrid heat pump is defined as follows: “A hybrid heat pump is the combination of an electric heat pump and a fossil-fueled boiler or furnace under a single optimized control strategy.” (Friedel, 2019). For the use case of our approach and the case study, we refine this definition. As a hybrid heat pump system, we consider the combination of an existing fossil-fueled boiler with a new heat pump, whereby the existing fossil-fueled boiler serves as the heating system for the residual thermal load.

Since the purpose of measures to reduce the space heating demand is to save useful energy, they are designated as saving measures (M_S). Saving measures intended to enhance the energy efficiency of the building envelope are designated as renovation measures. Measures to decarbonize the heat supply for space heating are labelled M_H.

1.2. Role-model function of the public sector

A comparative analysis of the primary regulations of the relevant institutional levels – the Energy Performance of Buildings Directive (EPBD) in the European Union (European Parliament, 2024), the Buildings Energy Act (Federal Ministry for Economic Affairs and Climate Action of Germany and Federal Ministry for Housing, Urban Development and Building of Germany, 2023) in Germany and the Climate Protection Pact (Federal State Baden-Württemberg of Germany, 2023) in Germany’s federal state Baden-Württemberg – reveals a common aspect: the public sector’s role model function. Since the public sector owns a significant number of buildings, it becomes imperative to assume the responsibility of serving as a role model. This underscores the necessity and need for action to implement retrofit measures to finally achieve carbon-neutral buildings. A considerable number of public buildings are owned and managed by municipalities. In Germany, municipal buildings comprise approximately 9% of the total non-residential building stock (Deutsche Energie-Agentur, 2018).

1.3. Hybrid heat pump systems

In order to address the inherent disadvantage of heat pumps, that their efficiency decreases considerably with declining temperatures of the heat source as well as with elevated temperatures in the heating system, the implementation of an additional heating system to cover the residual thermal load at low outside temperatures can be a beneficial solution. Especially in buildings with a high specific demand for space heating, the sole use of a heat pump can result in high investment expenditures due to the high thermal power needed for the heat pump, which is associated with high electricity costs during the winter months. Therefore, hybrid heat pump systems are an appropriate heating solution if it is not possible to reduce the specific space heating demand of a building to an extent that can be covered solely by a new heat pump as a new heating system (Oeko-Institut, Fraunhofer, 2022). The hybrid heating system can be configured either monoenergetic, equipped with an electric immersion heater, or bivalent, incorporating a secondary non-electricity-based heating system, such as a fossil-fueled existing boiler (see Section 1.1). Although there is no trend toward hybrid heat pump systems (Pehnt, 2024), they can be well combined with a roadmap of saving measures. In this case, the existing fossil-fueled system remains operational to cover the residual thermal load until the renovation measures have decreased both the space heating demand and the heating circuit temperatures sufficiently for enabling the heat pump to provide the total desired thermal power according to its maximum supply temperature. This approach enables the installation of a heat pump at an early stage, whereby the dimensioning of the heat pump is conducted with reference to the building’s final post-retrofit state, which incorporates the roadmap of saving measures.

1.4. Aim and structure of this article

The outlined importance of investments for retrofit measures to achieve climate goals, especially for public buildings, is accompanied by the challenge of limited investment budgets (Pannier et al., 2021; Staniaszek et al., 2021). This extends the need not only for suitable combinations of retrofit measures but also for structured retrofit roadmaps that distribute investments over time to tackle the financial constraints. Such retrofit roadmaps imply a transition period during which the space heating demand gradually decreases while the heating system must constantly guarantee the heat supply, even though it is also affected by the transition. If the heating system is not changed before or after implementing all saving measures, an optimal sizing is not possible. This

issue can be addressed with hybrid heating systems, whose main heating system may be a heat pump. In order to achieve the aim of proposing an approach that facilitates viable economic decisions for the measures of a retrofit roadmap, we present a methodology that combines and interweaves the techno-economic assessment of both single retrofit measures and the entire set of measures with a detailed simulation of the hybrid heat pump system under changing conditions caused by different stages of implemented retrofit measures.

Specifically, the following measures are considered and applied to a case study to illustrate the methodology.

- Installation of an air-to-water heat pump(M_H-HP)
- Operating the existing boiler(M_H-EB)
- Renovation of the roof(M_S-Ro)
- Renovation of the outer walls(M_S-Wa)
- Renovation of the windows(M_S-Wi)
- Installation of a new ventilation system with heat recovery(M_S-VS. HR).

The literature review (chapter 2), divided into related research of the partial methodological approaches (Sections 2.1.1 and 2.1.2) and condensed in the research gap (Section 2.2), is followed by the methodology (chapter 3). After an overview (Section 3.1), the main methodology is presented (Sections 3.2–3.4) before concluding with the methodology for deriving and selecting scenarios (Section 3.5). The application to the case study (chapter 4) is divided into the subchapters data set, scenarios, results, and discussion. The article is completed by the conclusion (chapter 5).

2. Literature review

2.1. Related research

As we present a combined approach, the literature review is divided into two sections: hybrid heat pump systems (Section 2.1.1) and the techno-economic assessment of retrofit measures with a special focus on the consideration of scheduling within this domain (Section 2.1.2).

2.1.1. Hybrid heat pump systems

A literature review from 2016 to 2022 dealing with hybrid heat pumps assisted by gas boilers in the form of case studies was conducted by Beccali et al. (2022). They analyzed various layouts, control strategies, and main performance indices related to energy, exergy, environmental, and economic performance. While several reviewed articles employed residential buildings as case studies, there is a paucity of literature that investigates hybrid heat pumps in non-residential buildings. Furthermore, interdependencies between hybrid heat pumps and renovation measures were not outlined in any of the reviewed articles. Before 2016, Klein et al. (2014) examined a full-year dynamic numerical simulation for a hybrid heat pump in accordance with our definition (existing fossil-fueled boiler and newly installed heat pump) by comparing the results for a residential building before and after renovation. The purpose of the approach was to analyze the influence of oversizing on the seasonal performance factor (SPF) and the coverage ratio (α_{HP}). Saffari et al. (2023) also considered hybrid heat pumps as a combined new heating system without an existing boiler by carrying out a techno-economic analysis for three retrofit levels of a residential building (case study). The authors point out that little research has been conducted on the integrated analysis of building retrofit scenarios and hybrid heat pumps. The scheduling and interdependencies between retrofit measures and hybrid heat pumps during the transition time were not treated.

The benefit of a hybrid heat pump in comparison to a monovalent heat pump with regard to the choice of the heat pump's cut-off temperature for a given bivalent temperature was outlined by Bagarella et al. (2016). In the event that a hybrid heat pump is selected, appropriate sizing of the heat pump can be derived. Our approach also addresses the aspect of an appropriate sizing, but in relation to a decreasing space heating demand due to the implementation of saving measures.

For hybrid heat pump systems, the control strategy plays a crucial role in realizing the intended benefits. Li and Du (2018), who are mentioned by Beccali et al. (2022), investigated both control strategies and the resulting economic benefits for the use case of hot water supply. They compared control strategies with and without the hybrid mode. In order to determine effective measures for mitigating load peaks in the electricity grid that are caused by heat pumps, Wüllhorst et al. (2025) assessed hybrid heat pumps and building retrofits as countermeasures.

2.1.2. Techno-economic assessment of retrofit measures

The field of research that deals with the techno-economic assessment of measures to enhance the building's efficiency is very similar in terms of the economic assessment, but widespread and differentiated concerning the focus and methodological approach of technical aspects. Table 1 provides a synopsis of the literature by pointing out the variety in the overall approaches.

Beyond the methodological approaches, the fact that techno-economic assessment of retrofit measures can refer both to single buildings and to building stocks, which in turn can vary from a couple of buildings to the building stock of an entire country, emphasizes the variety of related work. A common characteristic of all approaches is the use of an optimization approach. Baldoni et al. (2021) and D'Agostino and Parker (2018) considered the so-called nearly Zero Energy Buildings (nZEB), which are defined by the European Union. While Baldoni et al. (2021) defined nZEB as the most ambitious of the four levels, D'Agostino and Parker (2018) focused on how the nZEB standard can be achieved cost-optimally, whereby the analyses were performed for an exemplary residential building in several European cities. Galimshina et al. (2021) took into account the entire life cycle of the building by conducting a life cycle analysis (LCA) and a life cycle cost analysis (LCCA), considering factors such as climate change, energy carrier prices, and gray energy as uncertainties. Renovation levels or depths were differentiated by Pannier et al. (2021), Baldoni et al. (2021), Galimshina et al. (2021), and Richarz et al. (2021). Ventilation systems, respectively heating, ventilation and air conditioning (HVAC) systems were partially considered. However, only Streicher et al. (2021) treated them as saving measures according to our definition (see Section 1.1) including the aspect of heat recovery. HVAC systems are regarded as part of the (building) energy system on the supply side for cooling (Pannier et al., 2021; Petkov et al., 2022). It is noteworthy that within the literature in Table 1, there is no overlap between single buildings as a case study and the consideration of HVAC systems.

The heat supply is never neglected in the considered synopsis of the literature. Although different heating technologies and a change of the present heating system are partially considered, a hybrid heating system is not incorporated. As previously stated in Section 2.1.1, extant literature focusing on hybrid heat pump systems does not adequately incorporate renovation measures.

The scheduling of retrofit measures can be differentiated into bundling and sequencing. In contrast to the scheduling of single buildings, the scheduling of building stocks not only refers to the question of when measures will be implemented (sequencing) and which measures will be implemented simultaneously (bundling), but also to the question of which building the measures are implemented on. Petkov et al. (2022) used a hybrid approach (deterministic and probabilistic), Pannier et al. (2021) employed bundling to reduce the search space while sequencing is determined by an action and an order chromosome to apply the NSGA-II algorithm afterwards. Both approaches yield Pareto-optimal results. Streicher et al. (2021) defined different measure packages that, together with other boundary conditions, lead to 1.1 million different schedules. Richarz et al. (2021) is, to our knowledge, the only article besides the related work of its corresponding author that

Table 1
Literature overview of related research on techno-economic assessment of retrofit measures. Abbreviations in table: Ro = roof, Wa = Wall,Wi = Window, Fl = Floorslab.

article	methods	case study	measures			scheduling
			building envelope	heating system	HVAC	
Baldoni et al., (2021)	cost optimal curves, stochastic LCC	residential building	Ro, Wa, Wi, Fl; 2 depths	gas boiler or heat pump	no	no
Galimshina et al., (2021)	LC(C)A, Monte Carlo Simulation, NSGA-II	2 residential buildings	Ro, Wa, Wi, Fl; 4 depths	gas/pellets boiler or heat pump	no	no
D'Agostino and Parker, (2018)	EnergyPlus, TRNSYS, simulation-based optimization	residential building	Ro, Wa, Wi, Fl; NZEB level	yes (unspecified)	NZEB compatible parameters	no
Petkov et al., (2022)	Multi-objective opt. (cost, CO_2)	4 residential and non-residential buildings	Ro, Wa, Wi	gas/oil/biomass boiler or gas CHP	yes, but as part of the energy supply	partly
Pannier et al., (2021)	NSGA-II based multi-objective opt., dynamic building energy simulation	2 social housing building stocks	Ro, Wa, Wi, Fl; 3 levels	gas boiler or district heating	yes, but not as saving measure	yes
Richarz et al., (2021)	MILP, dynamic building simulation (Modelica)	non-residential building	Ro, Wa, Wi; 2 depths	various common	no	yes
Streicher et al., (2021)	dynamic stock model, cash flow model (exogenous effects), optimization model	Swiss building stock	Ro, Wa, Wi, Fl;	gas/oil boiler, heat pump, district heating	yes, saving measures (with and without heat recovery)	yes

incorporated scheduling for a single building. The authors employed a mixed-integer linear programming (MILP) optimization approach to identify the optimal schedules based on optimization decisions, leading to Pareto-optimal results from economic (cost-optimal) and ecological (minimizing CO_2 emissions) perspectives.

Of the literature in Table 1, only Pannier et al. (2021) incorporated a focus on barriers or constraints, considering limited financial budgets. However, Richarz et al. (2023) included the shortage of craftworkers and the limited resources of energy carriers for heating systems as constraints to their methodology.

2.2. Research gap and uniqueness of this combined approach

Based on the outlined objective delineated in Section 1.4, the following requirements must be met for an appropriate approach: The consideration of all relevant retrofit measures, a techno-economic assessment of both single retrofit measures and the measure set, incorporating scheduling, as well as focusing on the hybrid heat pump system and its interdependencies with saving measures.

As stated in Section 2.1.2, the existing literature that incorporates saving measures, meaning both renovation measures and ventilation systems with heat recovery, is limited. Studies dealing with hybrid heat pump systems address saving measures only partially, but concentrate on the hybrid heat pump (Saffari et al., 2023). The extant literature that provides techno-economic analyses of retrofit roadmaps predominantly considers heating systems; however, there is a dearth of literature on the subject of hybrid heating systems, particularly hybrid heat pumps. In conclusion, to our knowledge, there is no existing literature that presents a techno-economic assessment of hybrid heat pump systems in combination with renovation measures including scheduling aspects.

The majority of the analyzed approaches are based on an optimization to find a cost-optimal solution. To incorporate realistic circumstances and constraints as well as impacts of one retrofit measure on others, which may imply opposing effects with regard to the profitability, a simulation approach is more appropriate. In practice, the decision regarding a building's retrofit roadmap is determined by many factors. Medal et al. (2021) classified the decision factors for energy efficiency retrofits as follows: economic feasibility, technical practicality, occupant impact, institutional characteristics, and environmental impact. Since it is challenging to translate all these decision factors into constraints using an optimization approach, a simulation-based approach is able to apply multiple predefined retrofit roadmaps that take into account all decision factors relevant to the specific case.

In summary, the objective of our approach is to interweave a techno-economic assessment of all retrofit measures that influence the space heating demand with a simulation of the heating system, including a heat pump, during the transition period. That results in a scenario-based framework that enables the consideration of drivers and barriers through the appropriate scheduling (bundling and sequencing) of measures.

3. Methodology

The combined approach yields several interrelated methodological modules, which are presented in Sections 3.1–3.5.

3.1. Overview

The combination of a techno-economic assessment of a bundle of retrofit measures, encompassing life cycle costing (LCC) during the utilization phase, with the simulation of a hybrid heat pump system (HP_sim) aims to unite a multi-year examination of a measure-based transition pathway of a building towards climate neutrality with a detailed annual hourly-based simulation of its heating system under changing conditions due to the transition. Before delving into the methodological modules, an overview of the comprehensive approach is presented to illustrate the interrelationships among the methodological modules, as depicted in Fig. 1.

The calculated space heating demand serves as a starting point for both the HP_sim and the techno-economic assessment. After being divided by the efficiency of the heat distribution, it is utilized as input data for the HP_sim, which passes the seasonal performance factor (SPF) and the coverage ratio (α_{HP}) – defined as the ratio of heat supplied by the heat pump to the total heat supplied by the hybrid heat pump system – to the techno-economic assessment. This allows for the calculation of the final energy required for space heating as well as the consumption-based cost and the CO_2 emissions for both the initial building state and various retrofit stages on an annual basis. Cost curves for the investment and, if relevant, operation and maintenance (O&M) costs complete the set of necessary cost parameters. Finally, annualized cost flows, net present values and levelized costs are determined.

Additionally, this is accompanied by a combinatorial analysis of

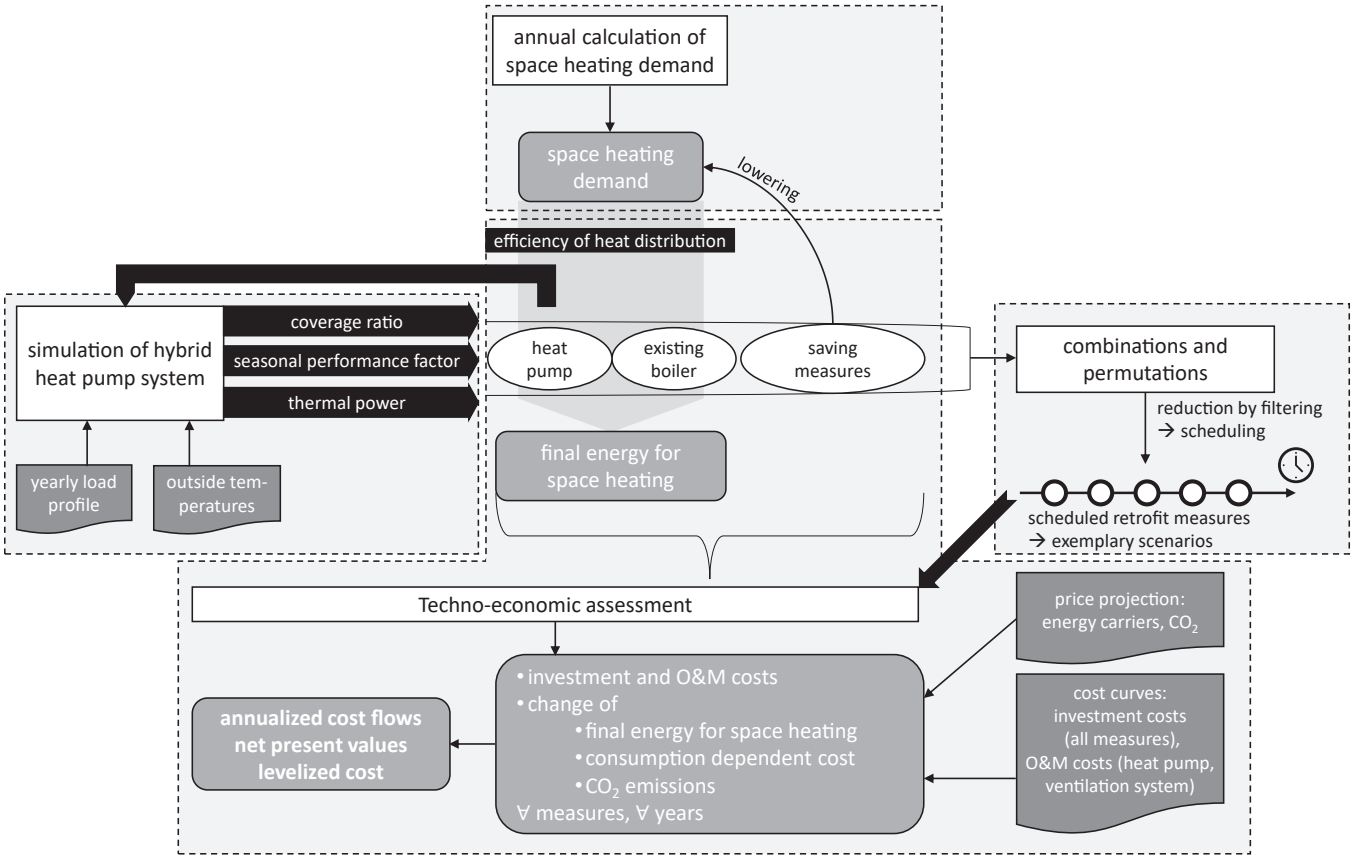


Fig. 1. Overview of the combined methodological approach.

possible schedules resulting from bundling and sequencing the single retrofit measures to derive exemplary scenarios through filtering.

3.2. Calculation of the space heating demand

The space heating demand Q_{SH} is the initial step in the calculation process and was determined with reference to the German standard DIN V 18599–2 (DIN V 18599-2 : 2018-09). The German implementation of the EPBD, the Buildings Energy Act, makes reference to this standard, which is methodologically analogous to the international standard ISO 52016–1 (ISO 52016-1 : 2018-04). The basic formulas are delineated in Equation 1.

$$Q_{SH} = Q_{sink} - \xi \cdot Q_{source} \tag{1a}$$

$$Q_{sink} = Q_T + Q_V + Q_{rest,sink} \tag{1b}$$

$$Q_{source} = Q_{solar} + Q_{I,source} + Q_{rest,source} \tag{1c}$$

The space heating demand Q_{SH} is defined as the difference between heat sinks Q_{sink} and heat sources Q_{source}, multiplied by the degree of utilization of heat gains ξ. The main heat sinks consist of the sum of transmission heat losses Q_T, ventilation heat losses Q_V and other heat losses, which are subsumed as $Q_{rest,sink}$, but were not considered in the analysis. Solar gains Q_{solar} and internal gains of electricity or persons $Q_{I,source}$ are considered in relation to Q_{source} (neglected heat gains are subsumed as $Q_{rest,source}$). All calculations were conducted on an annual basis, employing local heating degree days to consider climatic variations for the entire building. In order to capture different types of heat emission, the area heated by radiators and the area heated by the ventilation system were distinguished, thus corresponding to a division into two functional zones. Furthermore, a distinction was made between normal operation while occupied and a reduced target temperature while unoccupied. The weighting was adjusted according to the annual hours of each operating mode. With regard to the ventilation system, the aforementioned distinctions are reflected in the parameters of air volume, air change rate, and air flow, thereby accounting for the underlying quantitative differences. The disparities between the DIN V 18599–2 and the ISO 52016–1, which are exemplified by the varying temporal resolution of the calculation approach (monthly and hourly method), are negligible in this context due to the annual examination (Sawachi, 2020).

The purpose of renovation measures is to decrease the heat losses by transmission through the building envelope; a ventilation system with heat recovery can diminish the heat losses by ventilation. On the whole, the implementation of saving measures leads to a reduction of Q_{sink}. The renovation of the windows is the only measure that directly affects the solar gains because of a changing g-value. Since ξ is influenced by the ratio of Q_{source} and Q_{sink}, it changes after each saving measure.

If the final energy consumption is available, the calibration of the space heating demand according to DIN V 18599-2 : 2018-09 can be proved with respect to the efficiency of the heating system and the heat distribution losses.

3.3. Simulation of a hybrid heat pump system

Since the techno-economic assessment of a hybrid heat pump system is strongly influenced by the SPF and α_{HP} of each heating system, a simulation was performed to deliver these two quantities as outputs.

The employed simulation model is based on correlation equations of air-to-water heat pump systems that were developed in a previous work (Kemmler and Thomas, 2020). The correlations are based on test bench data from 25 air-to-water heat pumps of different suppliers, which

describe characteristic maps, with median deviations of 2.6% for thermal output and 6.4% for COP, respectively. The operation periods of the heat pump and the fossil-fueled boiler were determined by calculating the energy balance for each hour of the year with respect to a representative and hourly heat load profile. The supply and return temperatures as well as the current COP (coefficient of performance) of the heat pump were derived from the corresponding outside temperature profile, which, for that purpose, also needs to be available in an hourly resolution. Part of the setup is a thermal energy storage (TES). The storage tank was dimensioned to store the amount of heat delivered by the heat pump for at least one hour at the lowest modulation level. Due to the consideration of a TES, the utilization ratio can be calculated referring to the heat pump alone by the SPF or referring to the system of heat pump and TES ($\zeta_{HP,TES}$). Fig. 2 illustrates the setup of the hybrid heat pump system and the difference between SPF and $\zeta_{HP,TES}$. Hereby, a plain connection point is selected for the heat pump and the secondary heating system, which is a simplification compared to the practical implementation where hydraulic separators or valves may be utilized.

Eqs. 2 and 3 describe the corresponding formulas for SPF and $\zeta_{HP,TES}$ as well as η_{EB} for the secondary heating system, which often is represented by the existing boiler (index EB).

$$\mathrm{SPF} = \frac{Q_{HP}}{E_{el,HP}} \quad \text{and} \quad \zeta_{HP,TES} = \frac{Q_{HP,net}}{E_{el,HP}} \tag{2}$$

$$\eta_{EB} = \frac{Q_{EB}}{E_{Fuel}} \tag{3}$$

For further calculations (see Section 3.4), $\zeta_{HP,TES}$ was used, which is always smaller than SPF.

The maximum supply temperature that the heat pump can reach to meet the space heating demand exclusively was fixed at 55°C. This serves as a good compromise with respect to the general ability of heat pumps for higher supply temperatures on the one hand and the lower COP and seasonal performance factors due to the higher temperature lift in the heat pump on the other hand. Above the maximum supply temperature, the heat pump and the fossil-fueled boiler operate in parallel. Consequently, the annual heat output of the hybrid heat pump system including the temperature dependency of the operation of the heat pump can be delineated by Eq. 4.

$$Q_{th,system}\left(t, \vartheta_{flow}\right) = \sum_{t=0}^{8760} \left(Q_{HP_t} + Q_{EB_t} \cdot \Theta\left(\vartheta_{supply} - 55°C\right) - Q_{loss,TES_t}\right) \tag{4}$$

with the Heaviside step function

$$\Theta\left(\vartheta_{supply} - 55°C\right) = \begin{cases} 0 \;\forall\; \vartheta_{supply} < 55°C \\ 1 \;\forall\; \vartheta_{supply} \geq 55°C \end{cases}$$

In addition, start-up losses were set at 5% and the minimum modulation level was set at 50%.

The operational pattern of the hybrid heat pump system depends on the supply temperature, which is, in turn, determined by the outside temperature assuming an outside temperature control of the heating system. By this means, any saving measure that reduces the transmission heat losses through the building envelope decreases the space heating load and allows for a reduction of the supply temperature of the heating system, as the existing heat exchangers (radiators) have to provide less thermal power. If the ventilation system serves as an air-based heating system, its requirement for the supply temperature is only the entering air temperature, augmented by the temperature spread of the water-to-air heat exchanger. Consequently, the ventilation system with heat recovery, which exerts an indirect influence on ventilation heat losses, is incapable of reducing the supply temperature due to its inability to influence the heat transfer at the radiators. However, the space heating demand can be reduced through the implementation of a ventilation system with heat recovery as the outside air is partially heated by the exhaust air. Where ventilation systems operate independently of the heating system yet in combination with a water-based heat supply, heat recovery leads to a reduction in the space heating load, which in turn indirectly permits lower supply temperatures.

The calculation of lowering the heating circuit temperatures follows Equation 5. $\Delta\vartheta$ is defined as the so-called excess temperature (Eq. 5b), $\dot{Q}_H$ is designated as the corresponding heat load. The reference (index N) signifies the dimensional parameters of the radiators, which include the supply and return temperature and the heat load of the initial building state. The exponent m depends on the type of heating surfaces. Since $\dot{Q}_{SH}$ is decreasing after a renovation measure, $\Delta\vartheta$ can also be diminished (Bader et al., 2021).

$$\Delta\vartheta_N = \frac{\left(T_{supply,N} + T_{return,N}\right)}{2} - T_{room} \tag{5a}$$

$$\Delta\vartheta = \Delta\vartheta_N \cdot \sqrt[m]{\frac{\dot{Q}_{SH}}{\dot{Q}_{SH,N}}} \tag{5b}$$

Given space heating loads, heat curves were determined for certain retrofit stages, characterized by the number of implemented measures out of the set of saving measures.

The representative load profile was based on a standardized heat

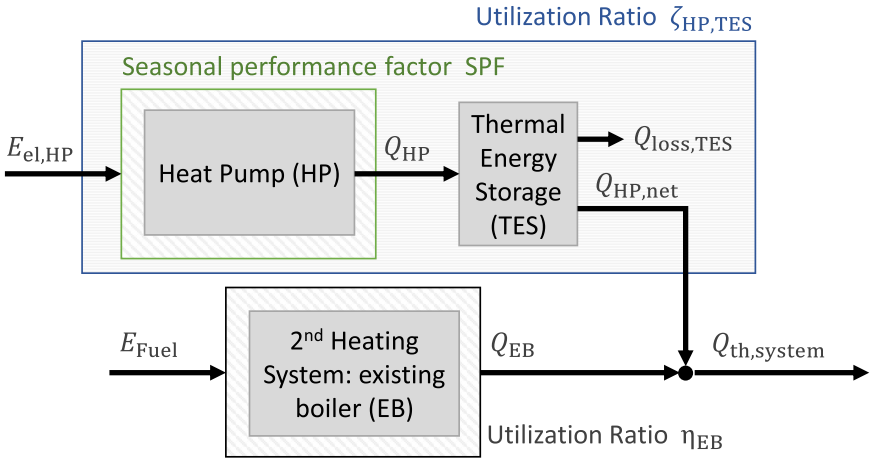


Fig. 2. Setup and energy input and output of the hybrid heat pump system highlighting the difference between seasonal performance factor (SPF) and utilization ratio $\zeta_{HP,TES}$.

load profile for gas boilers, reflecting the usage profile of the building type in the case study (Bundesverband der Energie- und Wasserwirtschaft e.V. et al., 2016). Since this load profile is not specified for space heating only, the share of domestic hot water was first estimated based on the summer heat load and then eliminated.

3.4. Techno-economic assessment

The techno-economic assessment constitutes the core of the presented multi-piece approach, as evidenced by its central positioning in Fig. 1. For this purpose, a Python-based tool was developed to model the energy and cost flows associated with the considered set of measures, which exhibit a high degree of interdependence. For instance, every measure affects the final energy consumption and CO_2 emissions in each year as well as the time series for $\zeta_{HP,TES}$ and α_{HP} of the hybrid heat pump simulation. In a previous work, parts of the methodology were already outlined (Schaffitzel et al., 2024).

With regard to the saving measures (index M_S), the cost savings C_{save} per year t over the technical lifetime T result from reducing the final energy consumption of each heating system (heat pump HP and existing boiler EB), considering different energy carrier prices p_{EC} and efficiencies ($\zeta_{HP,TES}$ / η_{EB}). To allocate the cost savings between the two heating systems, the annual space heating demand reduction potential caused by the saving measure, $\Delta Q_{SH}|_{M_S}$, is weighted by α, whereby α_{HP} and α_{EB} sum to 1. The complete formula is provided in Eq. 6. A (partial) change in the energy carrier leads to cost savings C_{save} if the ratio of energy carrier price to efficiency of the new primary heating system (index M_H) is greater than the corresponding ratio of the old secondary heating system in year t. In other words, cost savings C_{save} occur if the difference between the two ratios is positive (Eq. 7).

$$\begin{aligned} C_{save,EC}(t)\big|_{M_S} &= C_{save,EC}(t)\big|_{HP} + C_{save,EC}(t)\big|_{EB} \\ &= \Delta Q_{SH}|_{M_S} \cdot \left(\frac{\alpha_{HP}(t) \cdot p_{EC,HP}(t)}{\eta_{heat_distr} \cdot \zeta_{HP,TES}(t)} + \frac{\alpha_{EB}(t) \cdot p_{EC,EB}(t)}{\eta_{heat_distr} \cdot \eta_{EB}} \right) \end{aligned} \quad (6)$$

$$\forall t \in \{t_0; t_0 + T\}$$

$$C_{save,EC}(t)\big|_{M_H} = C_{save,EC}(t)\big|_{HP} = \frac{Q_{SH}(t)}{\eta_{heat_distr}} \cdot \alpha_{HP}(t) \cdot \left(\frac{p_{EC,HP}(t)}{\zeta_{HP,TES}(t)} - \frac{p_{EC,EB}(t)}{\eta_{EB}} \right)$$

$$\forall t \in \{t_0; t_0 + T\} \quad (7)$$

Implementing M_S-VS.HR reduces not only the space heating demand, but also the electricity consumption of the fans due to an enhanced specific fan power (SFP), which leads to additional savings in energy carrier costs.

The calculated economic quantities include annuities (for positive and negative cost flows), net present values (NPV) as well as levelized costs and payback times. The approach of levelized costs to assess the profitability of retrofit measures is described in more detail as follows.

The levelized cost of heat (LCOH) is frequently determined for the techno-economic evaluation of heating systems for the heat supply of buildings. The calculation determines the ratio between the present value of heat supply costs and the present value of the amount of generated heat over the heating system's technical lifetime (Louvet et al., 2017). LCOH facilitate a comprehensive comparison of diverse heating systems. In the event that the heating system, respectively the main heating system in the case of a hybrid heat pump system, is changed, two distinct heating system technologies are relevant. Consequently, the definition of the LCOH must be adapted to evaluate a retrofit measure. The LCOH of the replacement of the (main) heating system was derived from the difference in the LCOH between the new and the old heating system. The replacement of the heating system is profitable if the sum of the present value of operating cost savings exceeds the investment, meaning if the net present value is positive. Therefore, the ratio of profit to benefit is considered instead of the ratio of costs to benefit. The levelized cost of changing heating system (LCCH) is calculated by dividing the net present value of implementing M_H by the present value of the amount of heat generated over the heating system's technical lifetime T (see Eq. 8). In a hybrid heat pump system, the total amount of heat generated is distributed between two heating systems. The negative sign in the denominator defines a negative levelized cost as profitable.

$$LCCH_{M_H}(i,T) = \frac{NPV_{M_H}}{-\sum_{t=0}^{T} \left(\left(\frac{Q_{SH}(t)}{\eta_{heat_distr} \cdot \zeta_{HP,TES}(t)} \right)_{M_H} \cdot \frac{1}{(1+i)^t} \right)} \quad (8)$$

In contrast to LCOH or LCCH, where the amount of generated heat is not constant over the years, an annual assessment is suitable for the calculation of the levelized cost of a saving measure. The so-called levelized cost of saved energy (LCSE) is not as common as the LCOH, but the calculation method can be found in Oberegger et al. (2020), where Eq. 9 refers to. The NPV is annualized with the annuity factor, which depends on the interest rate i and the technical lifetime T.

$$LCSE_{M_S}(i,T) = \frac{NPV_{M_S} \cdot AF}{-\left(\Delta Q_{SH}(t)|_{M_S} \right)} = \frac{NPV_{M_S} \cdot \frac{i \cdot (1+i)^T}{(1+i)^T - 1}}{-\left(\Delta Q_{SH}(t)|_{M_S} \right)} \quad (9)$$

In contrast to LCOH, LCSE and LCCH are building-specific indicators. Accordingly, they cannot claim to be representative. While the objective of LCOH is the holistic assessment of heating system technologies, LCSE and LCCH serve as indicators that contribute to investment decisions of building owners.

The profitability of a retrofit measure can be derived from the NPV, LCSE/LCOH or the payback time and is given if one of the following conditions is fulfilled: NPV > 0, LCSE/LCCH < 0, $t_{payback} < T$.

3.5. Permutations and combinations of measure bundling and sequencing

A schedule of retrofit measures can be derived employing either a deterministic or a probabilistic approach (Petkov et al., 2022). We apply the techno-economic assessment to a predetermined schedule, characterized by a fixed sequence and a defined implementation date for each measure, which corresponds to a deterministic definition of the schedule. It is not intended to apply the techno-economic assessment to all possible variants and to identify the optimal variant in terms of costs or CO_2 emissions, but rather to compare several realistic scenarios. In order to comprehend the range of possible schedules, the number of possible permutations and combinations was deduced. A combination is defined as a set of bundled or unbundled retrofit measures that is characterized by the number of bundles, the size of each bundle and the distinct retrofit measures within each bundle. A permutation is defined as a combination that is unique to the sequence of the bundles. Table 2 provides an overview of the possible number of bundles N_B through picking (number of different shades of gray per row) and the corresponding bundle sizes (number of measures/columns with the same shade of gray per row) for each combination. The measures are only labelled with numbers because the type of measure is not relevant.

The following equations are formulated for a set of five measures.

Eq. 10 describes the combinatorial number of distinct bundling options n_{bundle} that can be obtained if k_{pick} of five measures are picked to compose one bundle. This process can be iterated as long as k_{pick} is greater than the number of remaining measures. By multiplying n_{bundle} for each pick in a bundle combination j and repeating this by summing up over j, the result is the number of all possible combinations (Eq. 11).

$$n_{bundle} = \binom{n_{measure}}{k_{pick}} \quad (10)$$

number of iterations = number of bundles N_B

Table 2
Possible combinations for picking bundles from a given set of five measures. Size of the bundle is represented in the shades of gray; number of bundles N_B in roman numerals.

Bundle combination j	M_1	M_2	M_3	M_4	M_5
1	I	I	I	I	I
2	I	I	I	I	II
3	I	I	I	II	II
4	I	I	I	II	III
5	I	I	II	II	III
6	I	I	II	III	IV
7	I	II	III	IV	V

$$n_{\text{Comb}} = \sum_{j=1}^{7} \left(\prod_{N_B} n_{\text{bundle}} \right) \tag{11}$$

The number of permutations is determined by the factorial of N_B.

$$n_{\text{Perm}} = N_B! \tag{12}$$

A permutation of one combination may be equal to a permutation of another combination. For bundle combination 7, even every permutation of a combination is equal to another combination. After the elimination of equal permutations, the number of all unique permutations ($n_{\text{perm,net}}$) and combinations, in other words, the number of all possible schedules, $n_{\text{schedules}}$, is equal to the sum of the product of combinations and permutations for each bundle combination j (Eq. 13).

$$n_{\text{schedules}} = \sum_{j=1}^{7} \left(n_{\text{comb}_j} \cdot n_{\text{perm,net}_j} \right) \tag{13}$$

4. Application to a case study: municipal sports and event hall

The methodology delineated in the previous chapter can, in principle, be applied to both residential and non-residential buildings, given that the considered measures are applicable. The case study was selected from a pool of municipal buildings based on the practical need for a retrofit roadmap. The case study building, a sports and event hall belonging to a school, was built in 1975 in the southern German city of Reutlingen. According to Institut Wohnen und Umwelt (2022), the corresponding archetype building is a sports hall built prior to 1978. The heat supply consists of an oil boiler that was installed in 2002. The heat distribution is based on both the original ventilation system (air-based), which does not feature any heat recovery, and radiators (water-based). Since it is located in a rural area, district heating is not considered as a likely option for the future. In light of the aforementioned circumstances, there is a great need for action regarding the implementation of the five retrofit measures introduced in Section 1.4.

4.1. Data set

4.1.1. Building, heating, and ventilation system properties

The calculation of the space heating demand Q_{SH} (Section 3.2) requires an extensive set of data of which the most relevant building-specific data are given in the upper section of Table 3. The key parameters of the heating and ventilation system can be found in the middle and lower sections of Table 3. If necessary, there is a distinction between pre-retrofit and post-retrofit values. The selection of the thermal power of the air-to-water heat pump is substantiated in Section 4.3.2 on the basis of the selected scenarios (Section 4.2.2).

For the initial building state, the following heating circuit temperatures were applied: a supply temperature of 75°C and a return temperature of 65°C for a heating limit temperature of 15°C. The heat is distributed by both the existing ventilation system and steel tube radiators (exponent of m = 1,39 (Bader et al., 2021), see Eq. 5b). As a representative load profile, a standardized time series for commercial buildings with gas boilers, cleaned by the domestic hot water share, was employed (Bundesverband der Energie- und Wasserwirtschaft e.V. et al., 2016). The emission factor of heating oil ($f_{\text{emis,oil}}$) is 318 $\frac{\text{g CO}_2}{\text{kWh}}$ (International Institute for Sustainability Analysis and Strategy, 2021). For the electricity supplied to the heat pump, a renewable energy tariff was assumed with an emission factor of 49 $\frac{\text{g CO}_2}{\text{kWh}}$ ($f_{\text{emis,el}}$) from the perspective of a life cycle analysis (Lauf et al., 2022). The technical lifetime of the retrofit measures is given in Appendix A (Table A-3).

Table 3
General information of the building serving as a case study including changing parameters due to the implementation of retrofit measures (pre-retrofit (pre), post-retrofit (post)), (Departement of Building Management Reutlingen, 2024a; Federal Ministry for Economic Affairs and Energy of Germany and Federal Ministry of the Interior of Germany, 2020; Jedek et al., 2015).

information	unit	value					
net floor area	m^2	888					
		roof:		outer walls:		windows:	
building envelope areas	m^2	852		612		240	
		pre:	post:	pre:	post:	pre:	post:
U-Values	W/(m^2K)	1.0	0.12	1.0	0.12	2.7	0.8
heated air volume	m^3	3100					
occupancy time	h/a	2000					
		existing oil boiler:			air-to-water heat pump:		
thermal power	kW_{th}	339			20		
efficiency	-	0.925			*results (Section 4.3.1)*		
		existing system:			new system:		
specific fan power (SFP) of ventilation system	Wh/m^3	0.8			0.3		
heat recovery efficiency	-	-			0.8		

4.1.2. Economic data

The necessary input data for the techno-economic assessment include the retail prices of relevant energy carriers, the German carbon tax, the interest rate as well as investment cost (plus subsidies) and O&M costs.

The retail prices of energy carriers and the carbon tax (Table A-1), the interest rate and the subsidies (Table A-2) can be found in Appendix A. The investment and O&M costs for the air-to-water heat pump were derived from cost curves using the variables thermal power and year of investment (Klimaschutz- und Energieagentur Baden-Württemberg, 2023).

The cost elements related to the investment costs of renovation measures can be divided into two groups (Jedek et al., 2015). First, there are cost elements from which savings in space heating energy and the corresponding cost savings result directly (energy-related extra costs). Second, certain cost elements are assigned to the building maintenance and do not entail cost savings due to a decrease in the space heating demand (maintenance costs). For a techno-economic assessment of renovation measures, only the energy-related extra costs may be consulted under the condition that the renovation measures do not induce maintenance costs. The share of energy-related extra costs in the total costs varies depending on the renovation measure. Table 4 shows the energy-related investment cost for the considered renovation measures and their share of the total costs. There is a lack of literature on the specific investment cost of ventilation systems. Jedek et al. (2015) conducted an analysis that is referenced by (Deutsche Energie-Agentur, 2024). If a ventilation system is newly installed, a network of pipes must be installed concomitantly, which enlarges the investment cost. Given that the case study building has already been equipped with a ventilation system (without heat recovery), the peripheral infrastructure, particularly the ductwork, is predominantly in place and any costs for maintenance or replacing components do not belong to the additional energy-related costs. For this reason, we refer to the data of recent projects of the municipal building owner of the case study building (Department of Building Management Reutlingen, 2024b). Non-energy-related costs were estimated. As well as the investment cost for renovation measures, they are given in Table 4.

4.2. Scenarios

4.2.1. Scenario selection through filtering of possible scheduling variants

The application of the methodology of Section 3.5 to determine the number of permutations and combinations of different scheduling variants ($n_{\text{schedules}}$) for a set of five measures results in $n_{\text{schedules}} = 541$.

In order to reduce $n_{\text{schedules}}$ considerably to deduce exemplary scenarios, filters are defined which incorporate realistic circumstances and barriers (Table 5).

For municipalities, insufficient renovation budgets are a substantial obstacle (Brand et al., 2024; Pannier et al., 2021). Despite the variation in initial investments across different measures, an absolute yearly budget was not assumed, but a limit on the size of the bundle was set (filter 1). In practice, the probability of a measure being necessary is determined by the lifetime of the components. Given that the existing boiler has already exceeded its lifetime according to VDI 2067-1:2012-09, M_H-HP to decrease α_{EB} was set to be part of the first or second bundle (filter 2). Furthermore, the implementation of the heat pump at an early stage contributes to the reduction of CO_2 emissions (filter 3). Besides M_H-HP, also M_S-Ro was set to be part of the first or second bundle because it is an enabler for a subsequent installation of photovoltaic (PV) on the roof, which is driven by the obligation to install PV after a fundamental roof renovation by law in the federal state of Baden-Württemberg in Germany (Federal State Baden-Württemberg of Germany, 2023).

After applying the aforementioned three filters, a total of 18 scheduling variants remain. By considering the number of years between implementing a measure bundle, the number of combinations and permutations would grow even more. To avoid this, an equidistant time between all measures of two years was assumed.

Table 4
Energy-related costs for investments in saving measures including their share of the total costs (Jedek et al., 2015; Deutsche Energie-Agentur, 2024; Department of Building Management Reutlingen, 2024b).

saving measure	specific energy-related extra cost for investment	share of specific energy-related extra cost for investment in total costs
	$\frac{€}{m^2}$ / $\frac{€}{\frac{m^3}{h}}$*	%
M_S-Ro	105	38
M_S-Wa	100	45
M_S-Wi	80	~ 13 (depending on window size)
M_S-VS-WRG	12,75*	85

Table 5
Filters to reduce the number of possible scheduling variants based on realistic circumstances and barriers.

Filter no.	description	purpose
1	Size of bundle (number of measures per bundle) ≤ 2	financial constraints
2	M_H-HP and M_S-Ro are part of the 1st or 2nd bundle	age of the existing boiler (M_HP), requirement for roof photovoltaic (M_S-Ro)
3	If size of bundle 1 or bundle $2 \geq 2$: M_H-HP is part of bundle 1 or 2	age of the existing boiler (M_HP), early reduction of CO_2 emissions due to the change of energy carrier

4.2.2. Selected scenarios

The criterion for selecting three of the remaining eighteen scheduling variants is comparability. The measures M_S-Wa and M_S-Wi, which are not affected by the filters, are not varied. For the saving measures M_S-Ro and M_S-VS.HR, three options are considered: One measure is part of the first bundle, the second measure is part of the second bundle and reverse as well as both measures are part of the same bundle (first bundle). The heat pump is incorporated into the first bundle if there is one saving measure, or into the second bundle if M_S-Ro and M_S-VS.HR are in the same bundle. In summary, three of the five retrofit measures are scheduled differently (M_H-HP; M_S-Ro, M_S-VS.HR) while M_S-Wa and M_S-Wi remain fixed as the last measures. Table 6 illustrates the resulting scenarios using a timeline.

4.3. Results

In accordance with the established methodology, the presentation of the results is divided into the simulation of the hybrid heat pump system (Section 4.3.1) and the techno-economic assessment (Section 4.3.2).

4.3.1. Simulation of a hybrid heat pump system

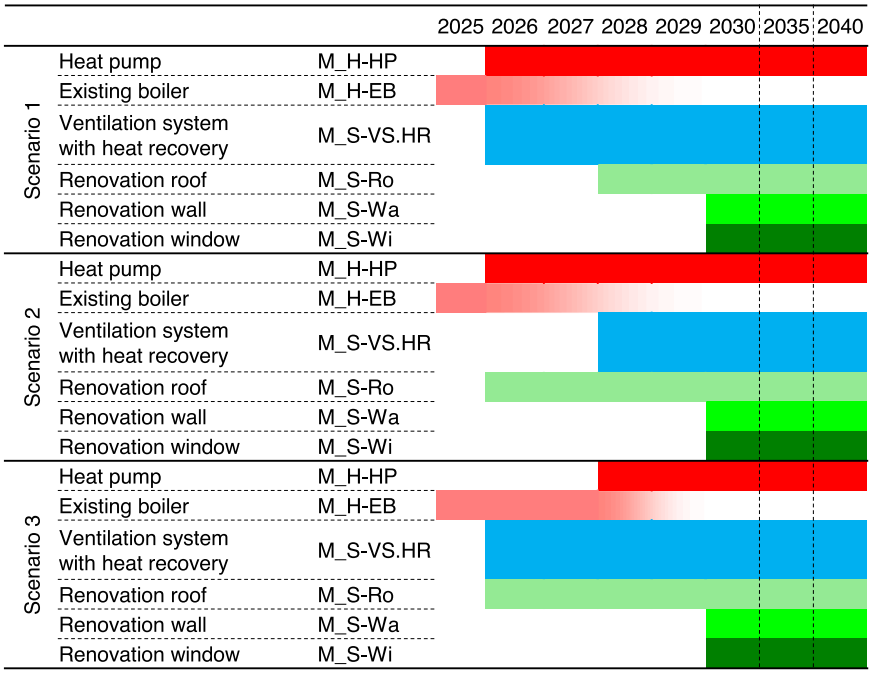
Regarding the selected scenarios in Section 4.2.2, the resulting combinations for the retrofit stages can be described with three Boolean variables X: X_M_S-WaWi, X_M_S-Ro, X_M_S-VS.HR. Each variable indicates whether one respectively two saving measures are implemented.

The number of combinations for three Boolean variables is 8 ($=2^3$). Given that the renovation of walls and windows is invariably scheduled last (X_M_S-Ro = false AND X_M_S-WaWi = true for X_M_S-VR.HR = true or false is not possible), a total of six combinations of different retrofit stages remain.

Fig. 3 shows the resulting supply and return temperatures and the corresponding space heating demands. As delineated in Section 3.3, the supply and return temperatures are solely influenced by the saving measures pertaining to the building envelope. The sole implementation of M_S-Ro, the first scheduled measure, results in a nearly equivalent decrease in the supply temperature as the implementation of M_S-Wa and M_S-Wi, the subsequent scheduled measures in conjunction.

The sizing of the heat pump is determined by the building's final post-retrofit state concerning its space heating demand. α_{HP} is a pivotal criterion of the hybrid heat pump system. In Fig. 4 (left), the coverage ratio α_{HP} is depicted for the six relevant retrofit stages, depending on the thermal power.

Table 6
Overview of the selected scenarios in a timeline.



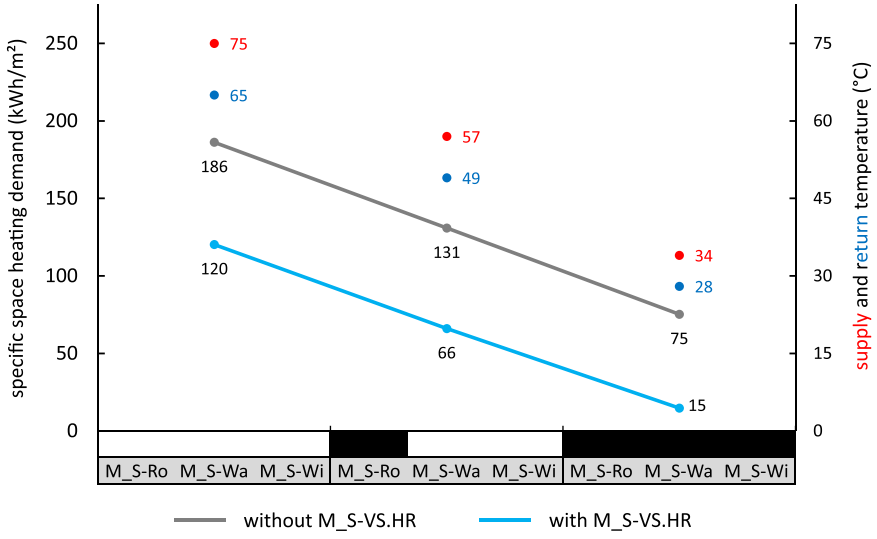


Fig. 3. Supply and return temperature of the hybrid heat pump system depending on the specific space heating demand of scenario-relevant schedules of measure bundles.

While the thermal power, which is necessary for α_{HP} of approximately 90% without any saving measures, is 60 kW_{th}, a heat pump of 10 kW_{th} is able to guarantee a monovalent operation (black-edged boxes, Fig. 4 (left)) on the condition that all saving measures are implemented. Moreover, for a monoenergetic operation (gray-edged boxes, Fig. 4 (left)) of the heat pump, at least one saving measure must be implemented. This presumes that the internal immersion heater of the heat pump has a maximum coverage ratio of approximately 5%. If no renovation measures are considered, which means that there is no decrease in the supply temperatures ("columns" 1 and 4 in Fig. 4 (left)), $\alpha_{HP} = 100\%$ cannot be achieved. Instead, saturation is achieved at approximately 90% and increasing the thermal power does not result in a notably higher coverage ratio.

Especially for a low space heating demand after the implementation of more than one saving measure, the advantage of an appropriately low thermal power is a high SPF. Fig. 4 (right) shows the SPF for the six relevant retrofit stages depending on the thermal power. The higher the thermal power, the lower the SPF due to a higher level of transient losses by on/off-operation. In contrast, the reduction in the heating circuit temperatures leads to an increase in SPF. If M_S-Ro and optionally M_S-VS.HR are implemented ("columns" 2 and 5 Fig. 4 (right)), the trade-off between a low thermal power and a high SPF emerges. With respect to the impact of M_S-VS.HR, it is conspicuous that the SPF is higher if M_S-VS.HR is not implemented. This is due to the fact that the average outside temperature during the heat pump operation periods is notedly higher if M_S-VS.HR is not implemented. An implementation of M_S-VS.

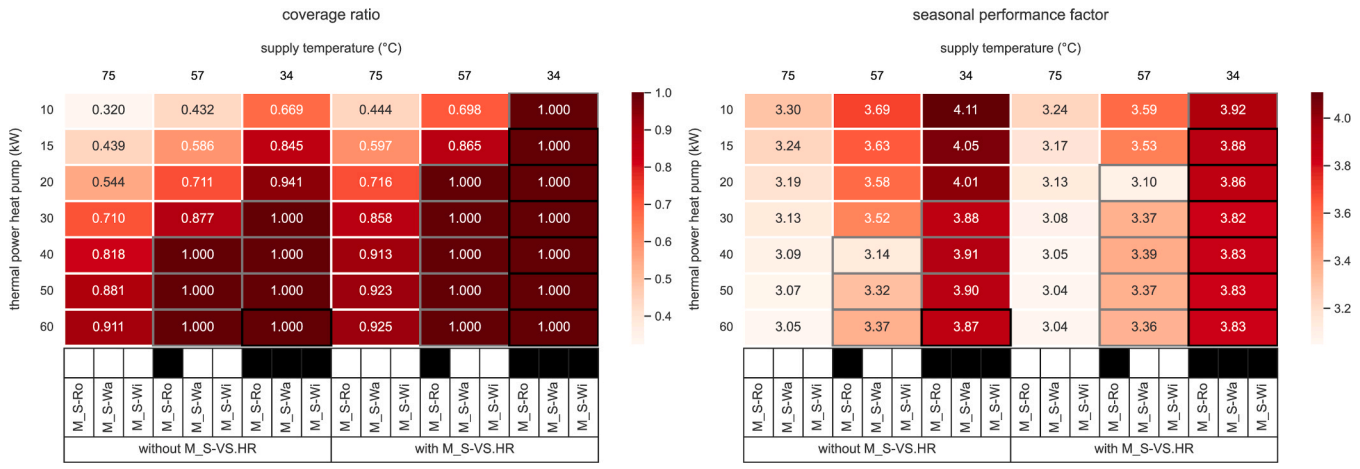


Fig. 4. Coverage ratio (α_{HP}) (left) and seasonal performance factor (SPF) (right) of the heat pump depending on the thermal power for scenario-relevant schedules of measure bundles; monovalent operation: black edged boxes, monoenergetic operation: gray-edged boxes.

HR results in an increase of α_{HP}, while the heating circuit temperatures remain constant. Hence, as the operation period shifts to lower outside temperatures, the efficiency of the heat pump will drop while the total operation hours will increase.

4.3.2. *Techno-economic assessment*

For each of the scenarios defined in Section 4.2.2, the techno-economic assessment was performed. Within the scenarios, the schedule of the retrofit measures is defined, but not the size of the heat pump. The thermal power of the heat pump should be of a size that the heat pump has a coverage ratio of 100% when all saving measures are implemented. In accordance with the results in Section 4.3.1, this is given for a thermal power of 10 kW_{th}. However, if the last scheduled saving measure(s) is/are not implemented, for instance, due to a lack of profitability, a 10 kW_{th} heat pump is too small. For the techno-economic assessment, the thermal power of the heat pump is set to 20 kW_{th}, which is the smallest value that ensures a monoenergetic operation of the heat pump if the renovation of the walls and windows is canceled or postponed (see Fig. 4 (left)).

While a saving measure decreases both the annual space heating demand and the CO_2 emissions, the implementation of the heat pump only decreases the CO_2 emissions as long as the ratio of the emission factors of the new and old energy carrier $\frac{f_{emis,el}}{f_{emis,oil}}$ is smaller than the ratio of the efficiencies of the new and old heating system $\frac{\zeta_{HP,TES}}{\eta_{EB}}$ which is given (see Section 4.1). Fig. 5 illustrates the development of the annual space heating demand and the CO_2 emissions over time according to the scenario-based schedules.

The impact of each measure is assumed to accrue linearly within the first year. As the set of measures differs only in terms of bundling and sequencing across the scenarios, the building's final post-retrofit state is the same for each scenario. Scenarios 1 and 2 exhibit a high degree of similarity because all measures are scheduled the same, except for the swap of M_S-Ro and M_S-VS.HR in 2028. The initial decrease in the space heating demand in scenario 3 is considerably higher than in scenarios 1 or 2 because a bundle of two saving measures (M_S-Ro, M_S-VS.HR) is implemented in 2026. Between 2026 and 2028, the sole investment in the heat pump leads to a decrease in CO_2 emissions, concurrent with a constant space heating demand.

In order to assess each retrofit measure within the set of measures, the LCSE respectively LCCH as well as the payback time are considered. Fig. 6 illustrates the retrofit measures with bubbles, whereby the size is proportional to the investment cost by plotting the payback time over LCSE/LCCH.

The profitability of a retrofit measure is contingent upon the fulfillment of two criteria: LCSE/LCCH < 0 and payback time $<$ lifetime. All measures except M_S-Wa are profitable as their bubbles are positioned to the left of the vertical zero line and below the corresponding horizontal line representing the technical lifetime. M_S-Wa is not profitable because it is scheduled last in all scenarios and its annual space heating demand reduction potential is lower compared to that of M_S-Ro and M_S-VS.HR. If M_S-Wa was implemented, every saved energy unit (kWh) would amount to 1.1 ct€. M_S-Wi is profitable, although it has the lowest annual space heating demand reduction potential due to the smallest building envelope area (see Table 3), but it can be implemented with very low energy-related extra investment cost. M_S-Ro and M_S-VS.HR are

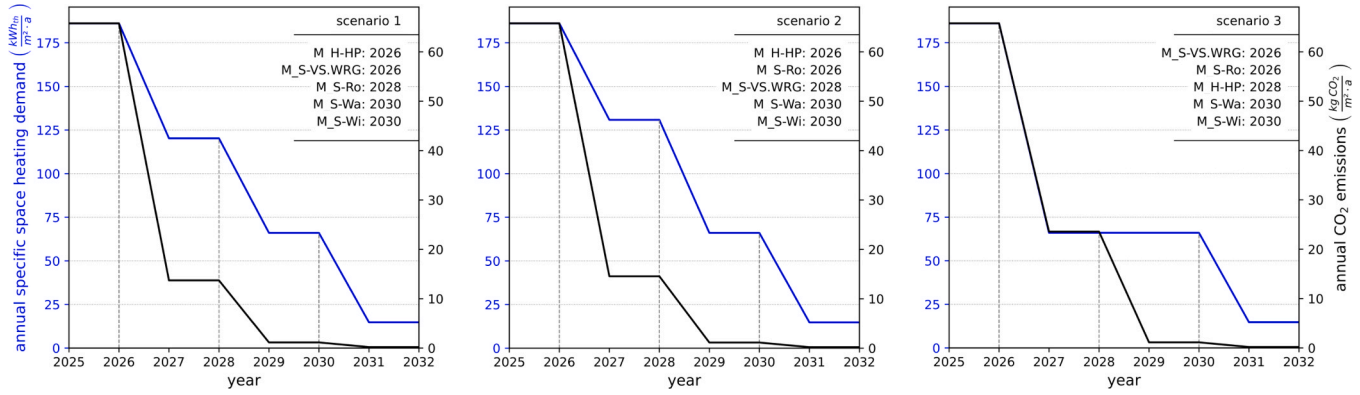


Fig. 5. Annual specific (referred to the net floor area) space heating demand (blue) and CO_2 emissions (black) for scenarios 1−3; vertical dashed lines represent years of measure implementation.

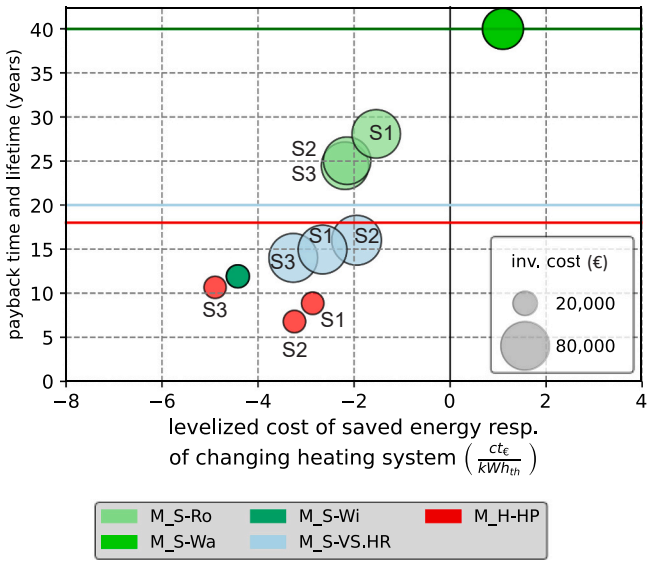


Fig. 6. Levelized cost of saved energy (LCSE) respectively of changing heating system (LCCH) and payback time for each retrofit measure for scenarios (S) 1−3. Lifetime of measures as horizontal lines colored according to the legend.

profitable as they are scheduled first or second (scenario 1 or 2) or both first (scenario 3). Moreover, these are the saving measures with the highest annual space heating demand reduction potential. The difference between the scenarios highlights the importance of the order of implementation of the measures: The earlier a measure is implemented, the more profitable it is. Compared to the saving measures, the investment cost of M_H-HP is lower, which is one reason for the scenario-independent profitability. M_H-HP is more profitable in scenario 2 than in scenario 1 as the displacement of heating oil is higher due to a greater $\zeta_{HP,TES}$ in the first two years, caused by the fact that the supply temperature can be lowered by M_S-Ro (first measure of scenario 2), but not by M_S-VS.HR (first measure of scenario 1). The lowest LCCH occurs in scenario 3 as $\alpha_{HP} = 1$ immediately after the implementation, which corresponds to a high amount of generated heat over the technical lifetime (denominator according to Eq. 8).

The implementation of a retrofit measure within a set of measures does not necessarily render the entire set unprofitable, which is demonstrated by Fig. 7.

As the NPV of the saving measures (green striped) of scenarios 1 and 2 is nearly equal, the higher NPV of the measure set in scenario 2 results from a higher NPV of M_H-HP, as explained in Fig. 6. The maximum NPV occurs in scenario 3, which is attributable to the bundling of M_S-Ro and M_S-VS.HR. The eminent annual space heating demand reduction potential corresponds to a substantial reduction in energy carrier costs and high NPVs of the single retrofit measures, making scenario 3 the most profitable as it is also the scenario with the lowest cumulative space heating demand during the transition period (see Fig. 5, integral area below the blue line).

Although the initial investment is the same for all retrofit measures in each scenario (except for the effect of discounting), the variation in scheduling results in different annual space heating demand reduction potentials of the saving measures as well as in different values of α_{HP} and SPF for the heat pump. With regard to the total costs, M_S-VS.HR is the saving measure with the lowest investment and nearly as effective as M_S-Ro considering the annual space heating demand reduction potential. By increasing the share of specific energy-related extra costs for investment in total costs, profitable saving measures could lose their profitability. Nevertheless, the differences between the scenarios remain. Consequently, the comparison of a normalized NPV, for example, by referring to the heated building area, as shown in Fig. 7, can quantify the impact of scheduling on the profitability of the measure set.

4.3.3. Sensitivity analysis

The results of the techno-economic assessment presented in Section 4.3.2 depend on the assumptions chosen for the input data, such as investment costs (see Table 4), retail prices of energy carriers and the carbon tax (see Table A-1), investment subsidies (see Table A-2), and the climatic conditions. This gives reason to investigate the influence of some of these parameters on the techno-economic analysis by examining a sensitivity analysis. According to Fig. 7, scenario 3 is characterized by the lowest NPV, making it the most economically viable scenario. Therefore, it is selected to serve as the baseline for the scenario analysis. The delineation of the scenarios is conducted by focusing on boundary conditions that relate to the tense relationship between climate action and economic viability. Against this background, the retail price of grid electricity, the carbon price or tax, and the investment subsidy are selected as parameters to be varied. Table 7 provides an overview of the derived scenarios and the corresponding variations of the parameters.

Table 7
Varied parameters and resulting scenarios for the sensitivity analysis.

sensitivity scenario	grid electricity – heat pump tariff*	carbon price / tax	investment subsidy
reference	no variation	no variation	no variation
price variation	- 3% p.a.*	+3% p.a.*	no variation
less investment subsidy	no variation	no variation	50% of reference
missing investment subsidy	no variation	no variation	none (0% of initial investment)

* from $t_0 + 1$ (2027)

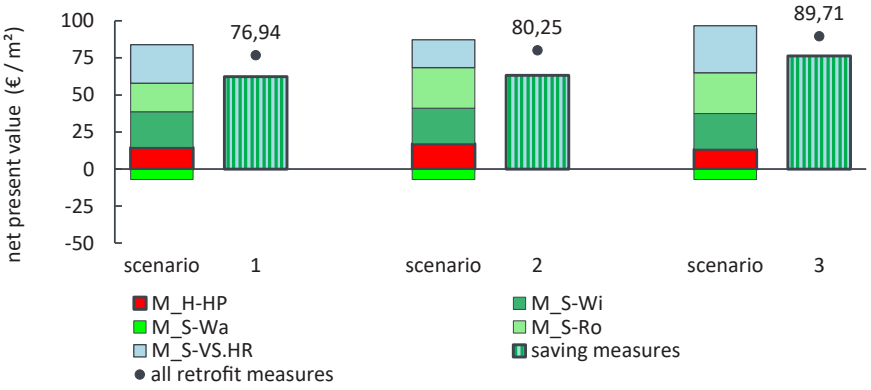


Fig. 7. Net present value of the single retrofit measures in the entire set of retrofit measures – scenario comparison.

For the scenario "price variation", the retail price for electricity is varied as a whole, whereas the variation of the retail price of heating oil refers only to the carbon price component. Since the carbon pricing will be determined by ETS 2 from 2027, significant price volatility is possible. The sensitivity of the investment subsidy is examined for two levels with less investment subsidy. As the NPV and the LCSE/LCCH are the primary output quantities of the techno-economic assessment, the sensitivity is applied to these two parameters for the scenarios shown in Table 7. Fig. 8 and Fig. 9 illustrate the results of the sensitivity analysis.

As revealed in Fig. 8 and Fig. 9, LCSE/LCCH and NPV demonstrate a substantially higher degree of sensitivity to variations in investment as compared to price variations. This finding also provided a rationale for the delineation of the scenarios. With regard to the aforementioned finding, a second scenario with price variation does not provide any additional insight. A variation in the energy-related costs for investments in saving measures was not considered, as the impact was found to be analogous to that of a variation in the investment subsidy.

While the price variation leads to an economic improvement of the LCCH, the opposite effect is observed for all LCSE (Fig. 8). This results from the fact that lower grid electricity prices and higher carbon prices, which in turn increase the retail price of heating oil, enhance the cash flow associated with the change in energy carrier when a heat pump is implemented. In the long-term, saving measures reduce the electricity consumption of the heat pump, which entails a lower cash flow when grid electricity prices are decreased. The effects regarding the NPV (Fig. 9) follow the same pattern. A reduction or complete removal of investment subsidies negatively affects the economic viability of all retrofit measures, with a greater impact occurring for measures with higher initial investment costs.

Apart from the economic input data, such as the investment cost, retail prices of energy carriers, carbon tax, and investment subsidies, the sizing of the heat pump also affects the results of the techno-economic assessment. In Section 4.3.2, the sizing of the heat pump is set at 20 kW_{th}, based on the requirement to ensure a monoenergetic operation of the heat pump even if only half of the saving measures are implemented. The investment cost is proportional to its specific power-related cost, which decreases with oversizing and increases with undersizing, according to literature-based cost curves (Klimaschutz- und Energieagentur Baden-Württemberg, 2023). The sensitivity of the α_{HP} and SPF for varying the thermal power of the heat pump is illustrated in Fig. 4. The effects of a different selection of thermal power, whether deliberate or a consequence of oversizing or undersizing, on both the LCCH and the LCSE of subsequent saving measures depend on the aforementioned parameters investment cost, α_{HP} and SPF. The sensitivity of both the heat pump-related parameters and the LCCH/LCSE to variations in the thermal power of the heat pump is delineated in Table 8.

If the heat pump is oversized, the LCCH decreases, thereby rendering the measure economically preferable. Firstly, this is attributable to the fact that the NPV of the retrofit measure increases, resulting from higher absolute investment costs. Secondly, the heat supply over the technical lifetime, denoted by the denominator of Eq. 8, increases due to a higher α_{HP}. Conversely, undersizing results in the opposite effect. In contrast to the sensitivity of the LCCH, an oversized heat pump enhances the economic viability of the saving measures. This effect is accompanied by a decline in the LCSE, as oversizing reduces the SPF. Consequently, the higher electricity consumption increases the cash flow of energy carrier cost savings. Conversely, when the heat pump is undersized, the SPF is higher and electricity consumption is lower. As a result, the cash flow from energy-carrier cost savings is reduced, leading to an increase in the LCSE and a deterioration of the economic viability.

5. Discussion

5.1. Generalization and limitations

According to Institut Wohnen und Umwelt (2022), there are approximately 78,000 buildings of the archetype building "sports buildings" in Germany, which gives an idea of the representativity of the case study. In addition to the building size, which is expressed as the net floor area derived from the number of floors and the base area, real buildings related to an archetype building differ from the archetype building itself in aspects such as the ratio of building envelope areas to the net floor area, occupancy patterns, and duration of use. The results presented in Section 4.3 refer to the case study and are not necessarily universally valid, which gives reason to check the case study's findings for transferability to non-residential buildings in general.

The parameters specific to the building examined in the case study that affect the calculation of the space heating demand, which in turn affects the energy carrier cost savings, are the initial space heating demand, the building envelope areas, the existing ventilation system and its operation pattern as well as the occupancy time and user behavior. The initial space heating demand and the building envelope areas can be compared to the characteristic values of a corresponding archetype building of a typology (Institut Wohnen und Umwelt, 2022). The U-values, the assumed efficiency of the existing boiler and the heat distribution, and costs are representative because they are based on literature. The final specific space heating demand of approximately 15 kWh/m^2 corresponds to the requirement of a Passive House (Passive House Institute, 2024). As thermal bridge losses are not considered and further inefficiencies due to the user behavior are likely, the hypothetical real final space heating demand might be higher. This also means that the profitability of the measures may be a bit worse than calculated and presented. Furthermore, the implementation of the considered set of measures for other non-residential buildings does not necessarily result in the Passive House level. The greatest source of uncertainty in calculating the space heating demand lies in the U-values of the initial building state. Due to an absence of building-specific data,

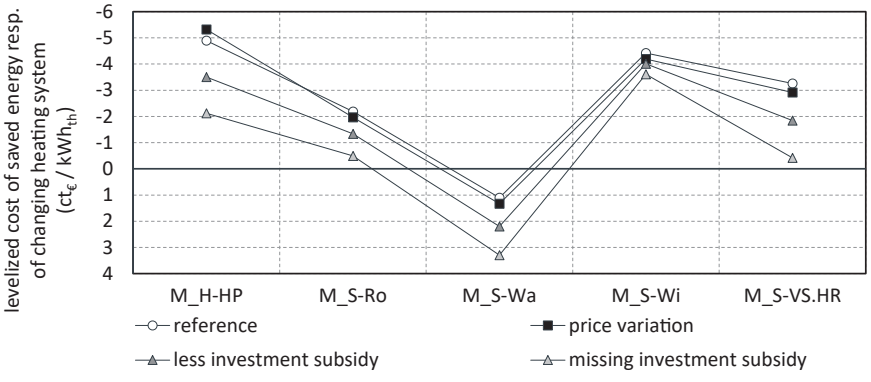


Fig. 8. Sensitivity of the LCSE respectively LCCH to electricity price, carbon tax, and investment subsidy.

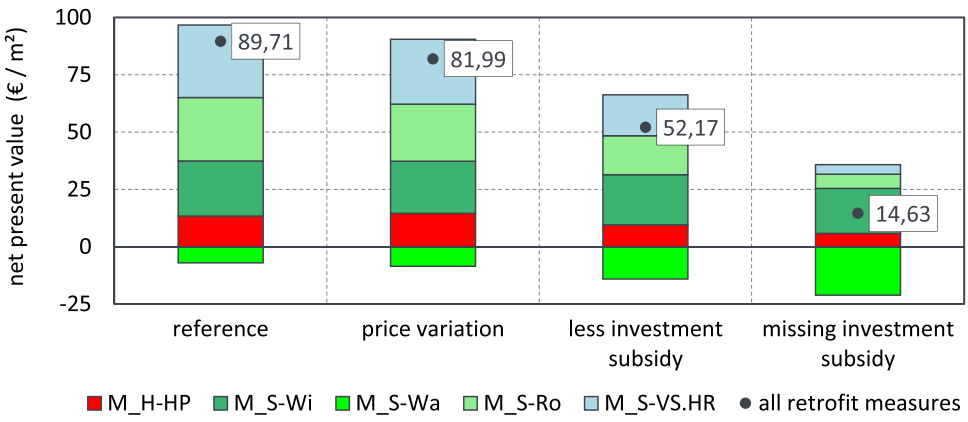


Fig. 9. Sensitivity of the NPV to electricity price, carbon tax, and investment subsidy.

Table 8
Sensitivity of heat pump-related parameters (investment cost, coverage ratio α_{HP}, seasonal performance factor) and the LCCH/LCSE to variations in the thermal power of the heat pump.

deviation of the thermal power of the heat pump	techno-economic parameter	change of techno-economic parameter
oversizing	investment cost of heat pump	↘ decreasing
	coverage ratio α_{HP}	↗ increasing
	seasonal performance factor SPF	↘ decreasing
	LCCH	↘ decreasing
	LCSE*	↗ increasing
undersizing	investment cost of heat pump	↗ increasing
	coverage ratio α_{HP}	↘ decreasing
	seasonal performance factor SPF	↗ increasing
	LCCH	↗ increasing
	LCSE	↘ decreasing

statistical data were utilized (Institut Wohnen und Umwelt, 2022). The calculated space heating demand is location-specific, as indicated by various parameters, including heating degree days, the length of the heating season, and solar irradiation. The contribution of heat sinks Q_{sink} to the space heating demand is proportional to the heating degrees, while solar radiation is a key factor in heat sources Q_{source} (see Equation 1). Consequently, while the space heating demand of a building can be determined for different climatic conditions, it cannot be scaled based on a single parameter.

Despite the advantages of a hybrid heat pump in conjunction with scheduled saving measures (see Section 1.3), there are also disadvantages and risks to be noted: A hybrid heat pump requires sufficient space to accommodate both the existing boiler and the heat pump, which is not always available in practical applications. The concurrent operation of two heating subsystems during the transition phase results in the duplication of maintenance costs. The study does not address how the existing boiler is specifically connected to the heat pump to form a hybrid heat pump system, both from a hydraulic and a control technology perspective. However, the proper operation of the heat pump, which involves switching and cycling, requires a more sophisticated control strategy than that required for a monoenergetic heat pump. It is advantageous to plan commissioning for the summer months, as installation-related shutdowns are not a problem during this period.

The coverage ratio of the internal immersion heater of the heat pump was presumed to be less than 5%. For any older and poorly insulated buildings, the implementation of saving measures prior to the installation of a hybrid heat pump is advisable to reduce high supply and return temperatures and to avoid a very low coverage ratio of the heat pump. Due to the implementation of retrofit measures over the course of several years, the installation phases are occurring more frequently. Therefore, it is imperative to ensure that the restrictions imposed on building occupants are minimized as much as possible. As the installation of rooftop PV is anticipated for the case study, a reduction in electricity costs can be expected. When combined with a battery storage, the electricity costs for operating the immersion heater during times of low outside temperatures become reasonable.

The techno-economic assessment is performed over the entire technical lifetime in terms of LCC. For this reason, and because reinvestments are neglected, salvage values do not need to be considered. Due to the different technical lifetimes (no unitary end of horizon) and the different levels of energy when calculating LCSE (useful energy) and LCCH (final energy), levelized cost for the entire set of measures cannot be determined. The results of the techno-economic assessment are highly influenced by the proportion of specific energy-related extra costs for investment in total costs, as indirectly demonstrated through the variation of the investment subsidies and analyzing the sensitivity to LCSE/LCCH and NPV (Section 4.3.3). However, differentiating cost elements is important for two reasons: maintaining value in the long-term and reducing the space heating demand. Building owners must raise the financial resources for the entire investment. Therefore, a holistic economic assessment would also have to take into account the expected impact on the value of the building besides the cost saving potential due to a decrease in the space heating demand (Azcarate-Aguerre et al., 2022). Further sensitive parameters of the techno-economic assessment include the price projection of energy carrier prices and the carbon tax (see Section 4.3.3), the interest rate, and the price change rate of investment cost.

Regarding the list of retrofit measures delineated in Section 1.4 and to be applied within the presented methodology, the list of measures to reduce the space heating demand could be extended. The insulation of the basement ceiling has been neglected due to the absence of a full-fledged, enclosed basement in the case study building. The potential for reducing space heating demand through building automation systems is highly dependent on the occupancy behavior, which tends to be overestimated because of simplifications in models (Vandenbogaerde et al., 2023). Due to the considerable uncertainties anticipated, building automation measures were not incorporated into the techno-economic assessment.

The domestic hot water supply, which requires considerably higher temperatures, could not be covered by the newly installed heat pump for space heating due to the low supply temperatures of the space heating system when reaching the final carbon-neutral building state. For the simulation of the hybrid heat pump, it is assumed that the hygienic generation of domestic hot water with the required high supply temperatures is covered by the existing oil boiler. Future alternatives

include a separate domestic hot water heat pump or a heat exchanger with a downstream electric water heater.

If rooftop PV were installed, which is legally required in the federal state of Baden-Württemberg after a fundamental roof renovation (Federal State Baden-Württemberg of Germany, 2023), the building's costs for electricity would be determined by a blended electricity price of self-consumption and grid supply. Since the levelized cost of energy for PV is consistently lower than the electricity tariff for grid supply (Kost et al., 2024), the effective price of electricity decreases. This effect improves the profitability of M_H-HP due to a higher price difference between heating oil and electricity, but lowers the profitability of the saving measures because the cash flow of energy carrier cost savings decreases.

In practice, building-specific constraints frequently arise with regard to the first measure due to structural damage or operational disruptions. The timing, sequence, and intervals of subsequent measures may be strongly influenced by the financial capacity of the building owner, such as municipalities, as evidenced by the case study. On a more general level, König et al. (2025) address the drivers and barriers in a city corporation to which the owner of the case study belongs.

5.2. Comparison with optimization-based approaches

In the context of retrofit roadmaps for buildings, optimization-based approaches typically aim to minimize costs. If multi-objective optimization is employed, CO_2 emissions are also minimized alongside costs (see Table 1). If the set of measures encompasses both saving measures and measures to change the heating system, a multi-objective optimization that minimizes CO_2 emissions and costs approach is deemed suitable, since there is a trade-off between reducing and decarbonizing the heat demand, which is exemplified as a Pareto front (Petkov et al., 2022; Richarz et al., 2021 in Table 1). Our approach pertains to a defined heating system, namely the hybrid heat pump, with the objective of conducting an analysis of its interdependencies to saving measures. The CO_2 emissions attributed to the hybrid heat pump are decreasing if a renewable electricity tariff is assumed, at least in the long-term. As a result, an optimization-based approach that shares our purpose and objective would not be required to be multi-objective regarding costs and emissions, but rather cost-minimizing. Our combined approach accounts for two crucial interdependencies: First, both the coverage ratio and the seasonal performance factor of the heat pump vary depending on the implemented saving measures. Second, the savings in energy carrier costs, which influence the economic viability of the saving measures, depend on the ratio of heat supplied by the heat pump and the existing boiler, given the differing energy carrier prices. These interdependencies among retrofit measures are difficult to represent adequately within an optimization framework, even though a myopic approach would be more appropriate than one based on perfect foresight.

As the efficiency of a heat pump (SFP) is usually part of the input data, optimization-based approaches that rely on perfect foresight require a projection of the SFP. However, this is incompatible with the SFP's dependence on the supply temperature, which is influenced by saving measures. A deterministic retrofit roadmap that specifies the type and timing of each measure enables the consideration of the aforementioned dependencies while simultaneously constraining the solution space, which we demonstrate with our combined approach.

Constraints that either restrict the financial budget or the amount of useful energy avoided by saving measures are of great importance for both simulation-based and optimization-based approaches, as they are the condition for staged retrofit roadmaps. After all, the results in Section 4.3.2 show that less staging and more bundling is more cost-effective.

6. Conclusion

This work presents an approach that integrates a techno-economic assessment of both single retrofit measures and the entire set of measures with a detailed simulation of a hybrid heat pump system across the successive stages of building retrofitting. The application of the methodology to a municipal sports and event hall yields in a scenario comparison of retrofit roadmaps. Each scenario corresponds to one specific schedule of the set of five retrofit measures. In order to address the impact of bundling and sequencing, a combinatorial analysis has been conducted. The incorporation of realistic barriers and constraints, such as limited financial budgets, were translated into a list of filters to reduce the vast array of possible schedules and to deduce the applicable scenarios for the case study.

If the application of the approach is intended to facilitate decision support, decision criteria become imperative. Considering saving measures, this can be the cost-benefit ratio, expressed in the LCSE, or the effectiveness, for instance, expressed in a ranking of the annual space heating demand reduction potential per saving measure. The results of the case study confirm the following general findings: The most effective renovation measure is not necessarily the one with the lowest investment. The larger the corresponding area of the building envelope, the more effective the measure, but the higher the initial investment. The first saving measure(s) result(s) in the greatest energy and cost savings, especially if the heating system with a rather low utilization ratio has not yet been changed. Investments in saving measures after the implementation of a hybrid heat pump have a noticeably lower emission reduction potential because the building's CO_2 emissions are primarily mitigated by changing the energy carrier. Apart from renovation measures, the implementation of a ventilation system with heat recovery only allows for a reduction in heating circuit temperatures if the heating system is exclusively water-based. The retrofitting of fans as part of the investment in a new ventilation system with heat recovery can also reduce the electricity demand. If the economically unfavorable measure (s) are not implemented, this affects the profitability of the other measures. Since the dependencies of all measures are considered, the positive cash flow due to a reduction in space heating demand decreases with every saving measure. The waiving of the last one or two saving measures keeps the cost-saving cash flow constant after the last implemented saving measures, except for discounting effects. The set of really implemented saving measures also affects the final building state. However, the heat pump can be sized according to the actual final building state, which decreases the investment cost due to a lower thermal power compared to the required thermal load of the initial building state.

The results of the techno-economic assessment are slightly sensitive to variations in energy carrier prices and the carbon tax. In contrast, the initial investment exhibits a substantially stronger influence on both LCSE/LCCH and NPV, as demonstrated by the variation of investment subsidies. A different sizing of the heat pump directly affects the specific investment costs as well as the coverage ratio and the seasonal performance factor of the heat pump. Oversizing decreases the LCCH and increases the LCSE of subsequent saving measures while undersizing has the opposite effect.

The findings of the exemplary scenarios show that this combined approach is able to incorporate crucial interdependencies between single retrofit measures as well as the impact of bundling and sequencing (scheduling) on the techno-economic assessment. A techno-economic

assessment of the set of measures required for carbon-neutral operation of a building, considering the space heating demand, can thus point out the most efficient transition pathway for non-residential buildings, taking into account financial constraints and technical necessities by the use of a scenario comparison.

Future research could further enhance the robustness of the underlying space heating demand calculation by employing more sophisticated thermal modeling approaches that explicitly account for zonal differentiation, inter-zone interactions, and dynamic thermal behavior in connection with a higher temporal resolution. Beyond the simulation-based approach applied here, an alternative research direction would be to formulate the problem as an optimization task. This approach could entail the endogenous determination of retrofitting, bundling, and sequencing decisions, thereby reducing or even eliminating the need for manual scenario generation and subsequent filtering.

CRediT authorship contribution statement

Bernd Thomas: Writing – review & editing, Supervision, Project administration, Funding acquisition. **Markus Blesl:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Christine Widmann:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Tim Schaffitzel:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Perplexity in order to analyze and compare related work. After using these services, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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.

Acknowledgements

The authors gratefully acknowledge the support of the Ministry of Science, Research and Art of the federal state of Baden-Württemberg in Germany for funding the research project ‘Klima-RT-Lab’ within the funding program ‘Living Lab Climate’ and thank the Department of Public Buildings and Facilities of the city of Reutlingen for providing data and supporting this article. All conclusions, errors or oversights are solely the responsibility of the authors.

Appendix A

Table A-1
Price projection of retail prices of relevant energy carriers and carbon tax (Meyer et al., 2024) Values between the given years were interpolated linearly, values after 2040 are extrapolated linearly

year	heating oil	grid electricity – heat pump tariff*	CO_2
	in €/kWh		in €/t CO_2
2025	0.092	0.257	55
2030	0.121	0.290	125
2035	0.144	0.296	200
2040	0.161	0.297	275

* the heat pump tariff refers to residential buildings and is assumed to be adequate for the case study’s non-residential building

Table A-2
Interest rate and subsidies for investment cost of retrofit measures.The investment costs of the measures are not exceeding the maximum eligible investment expenditures

Parameters of fiscal measures	value	reference
Interest rate	3%	set value
Subsidy rate – investment new heat pump	30%	Federal Ministry for Economic Affairs and Climate Action of Germany, 2023
Subsidy rate – investment saving measures	20%	

Table A-3
Technical lifetime of the retrofit measures

retrofit measure	technical lifetime	Reference
	in years	
M_H-HP	18	Association of German Engineers, (2012)
M_S-Ro	40*	Federal Institute for Research on Building, Urban Affairs and Spatial Development of Germany, (2017)
M_S-Wa	40*	
M_S-Wi	40*	
M_S-VS.HR	20	Association of German Engineers, (2012)

*choosing one common value for better comparability, according to differing values in (Federal Institute for Research on Building, Urban Affairs and Spatial Development of Germany, 2017)

Data availability

Data will be made available on request.

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