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Quantifying Demand Flexibilities of Buildings for an optimal Design and Operation of integrated District Energy Systems

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Abstract:

The EU's ambitious climate targets have highlighted the need for novel methodologies in the integrated energy system planning and the development of sector-coupled operation strategies. In order to balance generation and consumption in the electricity grid with a high share of renewable energies, energy storage potentials have to be utilized across all sectors and new demand-side management strategies have to be developed. The energy storage potentials of buildings could benefit the grid stability and support the exploitation of renewable energy sources. Still, these potentials are not well quantified and are not considered in today's planning methods for district energy systems. This paper presents the derivation of widely applicable linear building models that capture both detailed demand characteristics and storage characteristics from dynamic building simulations, while accounting for thermal comfort. These models are integrated into linear energy system optimization models, enabling the hourly optimization of air source heat pump operation and the heat emittance into the buildings. The resulting approach allows for the quantification of flexibility indicators and provides insights into efficient operation strategies for buildings with varying thermal characteristics. The results indicate that all investigated buildings show economically viable potential for utilizing their thermal flexibility. While well-insulated buildings demonstrate higher potential for longer-lasting preheating and storage periods, still buildings with poor or moderate insulation also offer potential for shorter periods of utilization.

Keywords:

Building demand flexibility; Building simulation; District energy system planning; Energy system optimization.

1. Introduction

With the agreement of the UN Climate Conference in Paris in 2015, 195 parties worldwide agreed to limit global warming to below 2 °C compared to pre-industrial levels and to reduce greenhouse gas emissions worldwide. As a result, with the European Green Deal, the EU has set itself the goal of zero net greenhouse gas emissions by 2050 [1]. This requires far-reaching measures in many areas and a drastic turnaround in the energy sector in particular. In 2019 over 53.1% of total final energy consumption in Germany was required for heating [2], with just 14.9 % coming from renewables [3]. This leaves the heating sector facing a challenging transformation. According to the German Ministry for Economic Affairs and Energy [4], the building sector, was the largest end energy consumer in Germany in 2020 with a share of 43.8 %, consisting of private households as well as commercial, trade and service properties. If the expansion of renewable electricity generation is driven forward, sector coupling technologies such as power-to-heat will strongly increase in importance [5]. Growing shares of renewable energy in the energy system lead to higher fluctuations in the power generation and creates a growing need to adapt the demand to the fluctuating generation. Therefore, demand side management of buildings, districts and district heating networks can play a crucial role in exploiting renewable energy sources.

1.1. State-of-the-art

According to the IEA-EBC Annex 67 [6], energy flexibility of buildings needs to be utilized across a large share of buildings and districts, in order to meet the minimum energy reduction to supply grid services and integrate sufficient amounts of renewable energy. The IEA EBC Annex 67 defines energy flexibility of buildings as: "*the ability to manage demand and generation according to local climate conditions, user needs, and energy network requirements. Energy Flexibility of buildings will thus allow for demand side management / load control and thereby demand response based on the requirements of the surrounding energy networks*." [6]. To provide demand side management, both energy and power adaptions of the demand side are of interest, as well as

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the time in which they can be provided [7]. Demand side management includes all measures modifying the demand, including permanent retrofitting measures like renovations [8]. Demand response on the other hand is a subset of demand side management and only covers non-permanent actions, including load shifting and load shedding [8]. In this terminology the energy flexibility of a building is understood as the potential for demand response actions. Therefore, energy flexibility of buildings can be provided on the one hand by storing energy in batteries, in hot water tanks or inside the thermal mass of buildings and on the other hand by shifting the generation in time or by switching to other generation sources [9].

1.2. Flexibility indicators

Reynders et al. [10] review common quantification methods for the flexibility of buildings and identify three common characteristics: *i) temporal flexibility, ii) amplitude of power modulation and iii) the associated costs*. Reynders et al. [11] introduce a generic quantification method for thermal energy flexibility in buildings. As a key indicator they define the available capacity for active demand response C_{ADR} which can be used to quantify upward flexibility and describes the amount of surplus heat, that is additionally emitted into the building before the demand is reduced:

$$C_{ADR} = \int_0^{I_{ADR}} \left(\dot{Q}_{ADR} - \dot{Q}_{Ref}\right) dt. \tag{1}$$

Where I_{ADR} is the duration of the active demand response, $\dot{Q}_{ADR}$ the adapted heat flow during the time of the demand response and $\dot{Q}_{Ref}$ the reference heat flow, that would occur without the demand adaption. They further introduce an efficiency indicator as the ratio between the demand reduction achievable through the demand response event and the additional demand required to achieve the reduced demand:

$$\eta_{ADR} = \frac{Demand\ Reduction}{Add.Demand} = 1 - \frac{\int_0^{\infty}\left(\dot{Q}_{ADR} - \dot{Q}_{Ref}\right) dt}{C_{ADR}}. \tag{2}$$

Kathirgamanathan and Péan et al. [9] analyse three adaptions of these indicators that are used in further literature [12–14]. They find that all indicators show relatively high robustness to different building types, climates and control schemes and consolidate a generic indicator for the available capacity as presented in equation (1). The indicator describing the efficiency of the demand response can vary between different applications and depends on the point of view of the stakeholder. Kathirgamanathan and Péan et al. show that different definitions are necessary to distinguish between downward flexibility, a shift of the generation to later times, and upward flexibility, a shift of the generation to earlier times.

A third indicator introduced by Reynders et al. [11] is the power shifting capability t_δ of the buildings. The power shift $\dot{Q}_\delta$ is described as the difference between the actual heating power during the demand response $\dot{Q}_{ADR}$ and the heating power that would occur during standard operation $\dot{Q}_{ref}$:

$$\dot{Q}_\delta = \dot{Q}_{ADR} - \dot{Q}_{ref}. \tag{3}$$

The power shifting capability t_δ is defined as the duration this shift can be maintained without violating the restrictions of the building zone temperature for thermal comfort:

$$t_\delta = t\left(\dot{Q}_\delta\right). \tag{4}$$

1.3. Quantification of flexibility in buildings

Vandermeulen et al. [15] evaluates the energy flexibility of buildings based on Belgian typologies with the flexibility functions introduced by [6]. They use a resistance-capacitance (RC) building models based on Protopapadaki et al. [16] and the DIN EN ISO 13790, which has been recently replaced by the DIN EN ISO 52016 [17]. Dréau and Heiselberg [18] assess the thermal flexibility of two representative buildings from the Danish building stock using detailed building simulations in EnergyPlus [19]. They show that poorly insulated buildings can still be modulated over a short period of time. Furthermore, they demonstrate that the heating system of well-insulated buildings can be shut off for more than 24 hours and the flexibility potential is highly influenced by the type of insulation and the heating emitter system. Yang et al. [20] analyse the thermal dynamics of low-energy buildings connected to a district heating system using detailed Modelica models. They optimize the strategy to unlock flexibilities inside a building connected to a district heating network using a variable heat price. Nevertheless, the planning of demand side response strategies for district energy systems is still in the beginning and planners and operators are missing the right tools to quantify the flexibilities of their district energy systems and identify potential savings in the energy import costs and investments. In addition to monetary reductions, modelling the flexibility of buildings can also identify more efficient integration strategies of available renewable energy sources.

1.4. Modelling the thermal flexibility of buildings in energy system optimization frameworks

There are lots of existing frameworks and different approaches to optimize the operation or the design of district energy systems. The most common approaches are mixed-integer linear programming (MILP) models and include linear formulations of components like sinks, sources, busses, transformers and storages. This allows the representation of most elements in an energy system. The application of these frameworks usually requires connecting and parameterizing these components to create the mathematical expression of the overall optimization model. Nevertheless, the structure of only a few abstract components in energy system optimization frameworks has its limitations. When it comes to characterizing flexibilities in the building operation, simple sinks with fixed demand time series are no longer sufficient. Therefore, [21] and [22] introduce a demand model in the optimization framework oemof [23], capable of providing upper and lower capacities for demand responses. Kotzur [24] includes a 5R1C building model in their frameworks that was introduced by [25]. Both use the indoor room temperature as a variable in their models and optimize the temperature inside certain boundaries. It allows a flexible operation of the heating system while integrating one capacity for the whole building. However, as shown in Bacher et al. [26], low order RC models are not always sufficient to represent the thermal dynamics of the buildings. Hence, these methods usually do not take into account the limitations in the power shift, which is caused by the inertia of the heat transfer mechanisms and the time required for the heat to reach the deeper parts of the buildings. This highlights the need for a procedure to estimate these limits and quantify the storage properties of the buildings. Therefore, detailed building models and simulations are necessary to quantify the heat transfer from the room into different layers of the building.

1.5. Quantifying thermal demand flexibilities for a selection of representative buildings

The aim of this paper is to quantify and analyze the thermal demand flexibilities of a selection of representative buildings in Germany, with a focus on utilizing the models in the diverse planning processes of district energy systems. Therefore, a procedure is presented to model thermal flexibilities in buildings for energy system optimization frameworks, using the building database TABULA/episcope [27] and the building simulation standard EN ISO 52016 [17]. The potential of utilizing the flexibility of the building selection is analysed in an existing energy system optimization framework and established flexibility indicators are calculated. By not being oversimplified and yet easy to apply, the method presented in this paper can assist planners of district energy systems to quantify the demand response potentials, identify optimal design and operation strategies or integrate new renewable energy sources more efficiently. This enables the evaluation of thermal flexibilities for diverse applications in the planning of district energy systems.

2. Method

In this section, a procedure is presented to quantify the thermal flexibility of a selection of buildings from the German building stock. First, the chosen buildings analysed in this work are presented. Then, the building simulation model is introduced, that is used to analyse the dynamic heat transfer mechanism for each building. Afterwards, a procedure to determine the thermal storage characteristics of the buildings is presented and the building model for the energy system optimization is displayed. Last, the chosen energy system optimization framework and the modelling approaches to quantify the thermal demand flexibilities of the buildings are presented.

2.1. Building selection

The analysis of heating demand flexibilities in domestic buildings is carried out for a selection of building types in Germany. The building information are based on data from the European building database TABULA/episcope [27]. A single-family house (SFH) built between 1958 and 1968 is chosen as a reference. This type of building accounts for the largest share of all residential buildings in Germany, at around eight percent [28]. In addition, two further SFH are chosen, built before and after the reference building age class. All buildings have a net floor area of 160 m² and are investigated in three states of insulation. The data for geometries, heat transfer coefficients, heat losses and internal heat gains can be found in [27]. Internal solar gains are determined in hourly time steps depending on all transparent surfaces and their tilts and azimuths, using test reference year weather data from the German meteorological service (DWD) for a representative year between 2031 and 2060 [29].

2.2. Building model

To analyse the dynamic characteristics of the buildings and calculate their heating demands, the buildings are modelled and simulated according to DIN EN ISO 52016 [17]. The procedure can be used for residential and non-residential buildings and allows hourly calculations of heating and cooling demands and indoor temperatures. The calculation methods include internal solar gains, ventilation, infiltration and internal heat gains. Each building can be modelled using several zones and opaque and transparent building elements. All opaque building elements are modelled in five nodes, representing the different layers of the components. All layers are set with a heat capacities and heat transfer coefficients depending on the structures of the elements. For the zone and for each node, an energy balance is set up, taking into account the heat transfer mechanisms of conduction, convection and radiation as well as heat storage properties. Effective heat capacities of all building components are assigned according to [17] for average construction types. For simplification, it is assumed that all buildings consist of one heated zone, four walls, two roofs and six window areas, with varying orientations, as well as one floor and one door. Given a certain input, the zone temperature and all node

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temperatures can be simulated. To calculate the heating demand required to maintain the set point of the indoor temperature, the energy balance of the zone can be solved for the heating and cooling demand $\dot{Q}_{demand,ref}^{building}(t)$. This modelling approach takes into account the inertia of the heat transfer mechanisms in the different layers of the building elements and is used quantify the heat demand flexibility in the buildings. It further allows to simulate ideal heating and cooling demands for fixed zone temperature setpoints.

2.3. Modelling building and it's flexibility in an energy system optimization framework

Due to diverse building types, building structures and refurbishment conditions, different buildings show varying dynamic characteristics in the heat transfer and the charging of their thermal masses. To quantify all flexibility potentials using the common indicators presented in 1, the demand response events need to be specified. An optimal demand response depends on several factors, including the availability of renewable energy sources, electricity price signals and building parameters such as insulation properties, heat capacities and current temperatures. All these variables influence the quantification of the flexibility indicators. Therefore, the buildings characteristics are integrated in a MILP energy system optimization that allows optimizing the utilization of the buildings flexibility in different applications. To model the heating demand as well as the thermal flexibilities of a building in an energy system optimization framework, a combination of a generic sink and a generic storage is selected. The chosen interconnection is shown in Figure 1. The sink is assigned with a demand time series $\dot{Q}_{demand,ref}^{building}(t)$, resulting from a building simulation based on [17] and taking into account detailed heat transfer mechanisms. The storage component is set to represents the deviation to the normal operation of the building and characterizes the additional heat storage properties and losses. It is therefore referred to as an additional virtual storage (vs). The additional heat losses of the building $\Delta\dot{Q}_{add\_loss}^{building}(t)$ and the losses of the virtual storage $\dot{Q}_{loss}^{vs}(t)$ correspond to the difference between the heating demand at an increased zone temperature $\dot{Q}_{in,increased}^{building}(t)$ and the heating demand at a normal operation $\dot{Q}_{demand,ref}^{building}(t)$:

$$\Delta\dot{Q}_{add\_loss}^{building}(t) = \dot{Q}_{loss}^{vs}(t) = \dot{Q}_{in,increased}^{building}(t) - \dot{Q}_{demand,ref}^{building}(t). \tag{5}$$

The virtual storage component is further defined by a loss rate r_{loss}^{vs}, a nominal storage capacity $C_{nominal}^{vs}$ and a limit in the inflow and outflow power $\dot{Q}_{charging}^{vs}$ and $\dot{Q}_{discharging}^{vs}$. The loss rate r_{loss}^{vs} is the fraction of lost energy per time. The heat losses of the virtual storage $\dot{Q}_{loss}^{vs}(t)$ can therefore be described as the product of the loss rate and the current energy content of the storage $E^{vs}(t)$:

$$\dot{Q}_{loss}^{vs}(t) = r_{loss}^{vs} \cdot E^{vs}(t). \tag{6}$$

Since both, the additional heat losses $\dot{Q}_{loss}^{vs}(t)$ and the storage level $E^{vs}(t)$, show an almost linear dependency on the temperature increase of the zone $\Delta T_{increased}^{Zone}$, the loss rate is assumed to be constant. It can be determined from the ratio between the maximum additional heat loss of the building with a zone temperature of 22 °C ($\dot{Q}_{loss,22°C}^{vs}$) and the storage capacity $C_{nominal}^{vs}$:

$$r_{loss}^{vs} = \frac{\dot{Q}_{loss}^{vs}(t)}{E^{vs}(t)} = \frac{\dot{Q}_{loss,22°C}^{vs}}{C_{nominal}^{vs}}. \tag{7}$$

The storage capacity is set to correspond to the amount of heat that can be stored inside the building and utilized at later times. It is therefore defined as the total heat demand decrease during the discharging event after the system is fully charged and the zone temperature is at its upper limit:

$$C_{nominal}^{vs} = \int_{I_{charged}}^{I_{discharged}} \left(\dot{Q}_{demand,ref}^{building}(t) - \dot{Q}_{in,decreased}^{building}(t)\right) dt. \tag{8}$$

While the heat flow $\dot{Q}_{demand,ref}^{building}(t)$ corresponds to heat demand that is necessary to keep the zone temperature at its lower limit in a static environment, $\dot{Q}_{in,decreased}^{building}(t)$ describes the heat demand that is necessary after the system is fully charged and has reached an equilibrium with a zone temperature at the upper limit. However, not only the storage capacity of buildings varies significantly with the year of construction and the level of insulation, but also the maximum heat flow that can additionally be emitted into the building during the charging process $\dot{Q}_{charging}^{vs}$ and the maximum heating power that can be used again at the discharging process $\dot{Q}_{discharging}^{vs}$ differ depending on the building. During the charging process, a high inflow rate can only be maintained for a short period of time, otherwise the energy cannot be transported into the deeper parts of the building and the zone temperature will exceed its limit. Therefore, a maximum heat input rate needs to be set for the internal storage component as well as a maximum heat output rate.

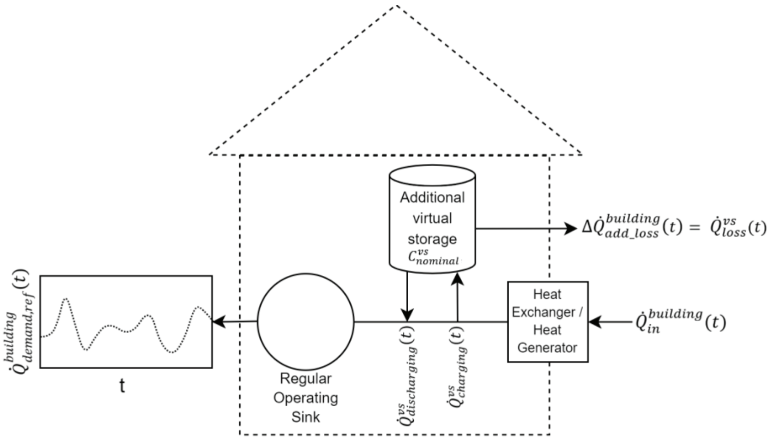

Figure 1. Approach to model the Buildings Demand and Flexibility Characteristics in the Energy System Optimization Framework.

2.4. Quantification of thermal storage characteristics

For the quantification of the storage characteristics of the buildings, building simulations are performed, in which the buildings are exposed to a lift in the indoor temperature setpoint. In this simulation, the ideal heat demand, required to maintain the zone temperature, is determined. Internal solar gains and internal heat gains are neglected in the static test environment, as for the quantification of the additional storage properties it is assumed that their influence on all zone temperature setpoints is equally effective. After an initialization period, to balance all heat transfer mechanisms, the zone temperature setpoint is lifted by a defined maximum temperature lift of 2 K from 20 °C to 22 °C. For another period, the required heat demand is calculated that keeps the zone temperature at the exact defined setpoint. The resulting demand profile defines the maximum heat input that can be emitted into the zone during an active demand response event, without exceeding the indoor temperature limit. Once the system is balanced again, the zone temperature setpoint is reset to 20°C and the reduced heat demand is calculated.

To parameterize the linear storage models of the buildings for the energy system optimization model, the additional storage capacity and the limits on the heating power must be set to constant values. Therefore, seven sets of storage parameters are determined from the simulation. Each set consists of the nominal storage capacity $C^{vs}_{nominal}$, the maximum charging heating power $\dot{Q}^{vs}_{charging,max}$, the maximum discharging heating power $\dot{Q}^{vs}_{discharging,max}$ and the heat loss rate. The sets are selected by varying the relation between the nominal storage capacity and the maximum charging heating power. The resulting relation describes the power shift capability t_{δ}, the duration in which the buildings can either be heated with the additional maximum charging power $\dot{Q}^{vs}_{charging,max}$ or the heat stored inside the building can be utilized again with the maximum discharging power $\dot{Q}^{vs}_{discharging,max}$, without exceeding the indoor temperature limits. In a linear building model, high power shift capabilities t_{δ} result in longer charging durations with lower maximum heating powers $\dot{Q}^{vs}_{charging,max}$, whereas low power shift capabilities result in the opposite.

If the power shift capability is fixed and the nominal storage capacity in this work is defined as the usable energy stored inside a building, the capacity can be determined by the product of the maximum discharging heating power $\dot{Q}^{vs}_{discharging,max}$ and the power shift capability t_{δ}:

$$C^{vs}_{nominal} = \dot{Q}^{vs}_{discharging,max} \cdot t_{\delta}. \tag{9}$$

For each set of parameters, a separate storage model is set up and used in the energy system optimization. This results in seven different flexible building models that are investigated in the following, representing different characteristics and utilization possibilities of the buildings. The best modelling approaches depend on the exact building type, its insulation, its storage properties and the exact application and are therefore analysed in an energy system optimization model.

2.5. Energy system optimization model

To determine optimal flexibility possibilities, the building characteristics, corresponding to the heating demands and the storage potentials, are integrated in the energy system optimization framework oemof [23]. The objective function is composed of the discounted investment costs of the heat generation plants c^{hg}_{inv} and the electrical energy purchases as shown in equations (10). The main additional constraints are stated in equations (11) - (13). An air source heat pump is selected as the heat generator using a variable coefficient of performance $COP^{hp}(t)$ depending on the outdoor temperature. The coefficient of performance is calculated using the correlations from [30]. The 2020 Day Ahead market prices are used as variable costs for electricity

$c_{el}(t)$. Further constant electricity levies, taxes and duties are neglected. The model optimizes the utilization of the buildings $\dot{Q}^{vs}_{charging/discharging}(t)$, the operation of the heat pump $\dot{Q}^{hp}_{out}(t)$ and the nominal heating power of the heat pump $\dot{Q}^{hp}_{nom}$ to minimize the costs for electricity C_{el} and the investment costs for the heat pump C^{hp}_{inv}:

$$\underset{\dot{Q}^{vs}_{discharging},\dot{Q}^{vs}_{charging},\dot{Q}^{hp}_{out},\dot{Q}^{hp}_{nom}}{\text{minimize}} \quad C_{total} = C_{el} + C^{hp}_{inv} = \sum_{t=0}^{8760} c_{el}(t) \cdot \frac{\dot{Q}^{hp}_{out}(t)}{COP^{hp}(t)} + c^{hp}_{inv} \cdot \dot{Q}^{hp}_{nom} \tag{10}$$

$$s.t. \quad \dot{Q}^{hp}_{out}(t) = \dot{Q}^{building}_{demand,ref}(t) - \dot{Q}^{vs}_{discharging}(t) + \dot{Q}^{vs}_{charging}(t) \tag{11}$$

$$E^{vs}(t) = E^{vs}(t-1) \cdot \left(1 - r^{vs}_{loss}(t)\right) - \dot{Q}^{vs}_{discharging}(t) + \dot{Q}^{vs}_{charging}(t) \tag{12}$$

$$\dot{Q}^{vs}_{discharging}(t) \geq 0 \text{ and } \dot{Q}^{vs}_{charging}(t) \geq 0 \text{ and } \dot{Q}^{hp}_{out}(t) \geq 0 \text{ and } \dot{Q}^{hp}_{nom} \geq 0. \tag{13}$$

The optimization is performed over a period of one year with time steps of one hour. First, for each building type and each state of refurbishment, a single optimization is performed to dimension the heat pump. Then, for each building the operation is optimized without including the investment costs for the heat generator. The results are used to calculate the annual costs reductions for electricity, when the flexibility is utilized, compared to the electricity costs of the same building without a flexible operation. Furthermore, an efficiency for the utilization of the virtual storage $C^{vs}_{nominal}$ is calculated that is based on equation (2). It is defined by the ratio between the total usable heat $\dot{Q}^{vs}_{discharging}$ and the heat that is additionally induced into the building $\dot{Q}^{vs}_{charging}$:

$$\eta_e = \frac{\int_0^{8760} \dot{Q}^{vs}_{discharging}(t)dt}{\int_0^{8760} \dot{Q}^{vs}_{charging}(t)dt}. \tag{14}$$

3. Results

In this section, the results of the individual building simulations and optimizations are introduced and the resulting flexibility indicators are presented. First, the building heating demands are presented under normal conditions without the utilization of their flexibilities. Afterwards, the results of the storage quantification procedure are displayed. Then, for all selected buildings and all storage model approaches the resulting nominal storage capacities, the maximum charging and discharging powers and the power shift capabilities are summarized. Finally, the flexibility efficiencies and the annual electricity cost savings are presented for all individual buildings.

3.1. Building heating demands

Figure 2 shows the heating demand time series $\dot{Q}^{building}_{demand,ref}(t)$ for the reference building in three different states of refurbishment under standard conditions and for a fixed indoor zone temperature. The influence of the insulation is shown in the reduction of the total heat demand as well as the reduced peaks.

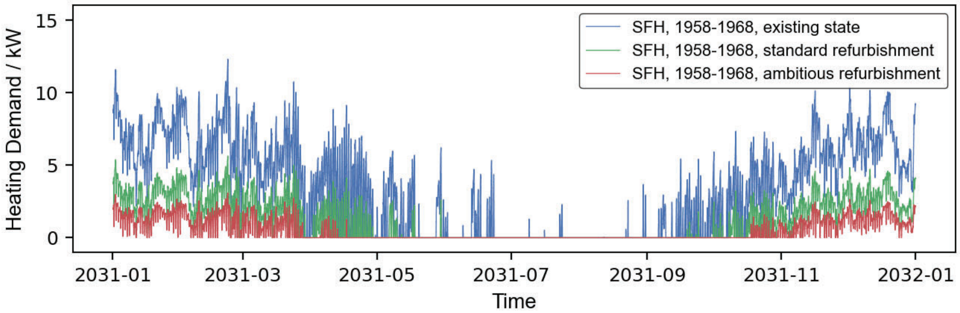

Figure 2. Heating demand time series for the reference single-family house built between 1958 and 1968 in three states of refurbishment, using weather data friom a test reference year from [29].

3.2. Quantification of individual building storage characteristics

Table 1 presents the results of the building simulations in the test environment. With a constant zone temperature of 20° C, each building balances at an individual constant heat demand $\dot{Q}^{building}_{const,20°C}$. When the zone temperature setpoint is raised from 20 °C to 22 °C, all buildings show an increase in the heat demand, that is required to meet the increased zone temperature setpoint. After reaching a maximum value of $\dot{Q}^{building}_{charge,max}$ instantly after the raise of the setpoint temperature, the demand decreases and diverges to a constant value at a zone temperature of 22 °C $\dot{Q}^{building}_{const,22°C} > \dot{Q}^{building}_{const,20°C}$. The profile describes the ideal heat input, that would keep the zone temperature at the upper value of 22 °C. The difference between the upper and lower constant heat demand $\Delta\dot{Q}^{building}_{22°C-20°C}$ describes the additional heat losses of the building, due to the increased zone temperature. The difference in the heating demand $\Delta\dot{Q}^{building}_{22°C-20°C}$ is nearly constant and almost independent of the ambient temperature, since it only describes the additional losses compared to the heating demand under normal conditions. When the building is in balance again, the zone temperature setpoint is set back to 20 °C and the heat demand decreases in analogy to the lift of the zone temperature setpoint.

Table 1. Overview of the heating power demands in the static test environment of the selected single-family buildings with a net floor area of 160 m² and in dependence of the additional storage model approach.

Building description			Heating power demands / kW				
Building Type	Age class	State of refurbishment	$\dot{Q}^{building}_{const,20°C}$	$\dot{Q}^{building}_{const,22°C}$	$\Delta\dot{Q}^{building}_{22°C-20°C}$	$\dot{Q}^{building}_{charge,max}$	$\dot{Q}^{building}_{discharge,max}$
SFH	1919-1948	Existing state	22.41	24.71	2.30	29.84	17.20
		Standard	7.45	8.32	0.87	14.58	0.0
		Ambitious	4.07	4.61	0.54	10.99	0.0
	1958-1968	Existing state	15.81	17.48	1.67	23.08	10.20
		Standard	6.98	7.81	0.83	14.04	0.0
		Ambitious	3.85	4.38	0.53	10.74	0.0
	2010-2015	Existing state	5.58	6.27	0.69	12.53	0.0
		Standard	4.93	5.57	0.64	11.88	0.0
		Ambitious	3.21	3.68	0.47	10.04	0.0

3.3. Quantification of capacities, maximum charging and discharging powers and power shift capabilities

The results are used to determine the storage nominal capacity $C^{vs}_{nominal}$, the loss rate r^{vs}_{loss} and the maximum additional charging and discharging powers $\dot{Q}^{vs}_{charging,max}$ and $\dot{Q}^{vs}_{discharging,max}$. All parameters are calculated depending on the power shift capability t_{δ}, as described earlier. The results define the storage properties of the flexible building models that can be integrated in the energy system optimization. Table 2 presents the nominal virtual storage capacities $C^{vs}_{nominal}$ for all buildings and the storage model approaches.

Table **3** shows the corresponding maximum charging and discharging heating powers. Poorly-insulated buildings show their highest usable storage capacity at low power shift capabilities. The SFH built between 1919 and 1948 in an existing state of renovation reaches a nominal storage capacity of 6.58 kWh and a maximum charging power of about 1.28 kW. On the other hand, well-insulated buildings can utilize more capacity when they are charged over a longer period. The building built between 2010 and 2015 with ambitious refurbishments shows the maximum usable storage capacity at a power shift capability of 8 hours and a maximum charging power of 0.91 kW. Each building shows an increase in the utilizable capacity when the state of renovations increases. In the same time, the loss rate decreases due the better insulation of the building envelope.

3.4. Energy system optimization results

The potential of utilizing the heating flexibility is analysed in the energy system optimization model for all building types, using the different sets of parameters for the additional storage component. Figure 3 shows the difference between the optimized heat input and the heat demand without utilizing the flexibility potentials of a single-family house built between 1958 and 1968 in a standard state of renovation. While the green areas correspond to the amount of heat that is additionally emitted into the building compared to the normal operation, the blue areas illustrate the optimized decrease of the heat input. The storage component is parameterized with a nominal storage capacity of 8.78 kWh, a maximum charging power of 2.13 kW, a maximum discharging power of 2.22 kW, and a power shift capability of 4 hours. The optimized heat input is the result of the energy system optimization, which minimizes electricity import costs and leads to fluctuations in the actual zone temperature. It is shown, that the optimized heat input deviates from the original demand during a typical week in the heating period. To validate the modelling approach and the optimized building operation, the optimized heat input is integrated into the building simulation model according to the DIN EN ISO 52016. The resulting zone temperatures from the building simulation are also shown in Figure 3. The temperatures vary between 19.7 °C and 21.75 °C. Figure 4 shows the optimized heat input and the resulting indoor temperature profile in the same week for the same building but without any renovation measures. The amount of energy that can be stored inside the buildings is less, due to higher losses through the building envelope. Still, a few hours during the week can be used to take advantage of a low electricity prices. The indoor room temperatures vary between 19.9 °C and 21.4 °C during the week. The optimal energy storage duration is also less due to the higher loss rate. On the other hand, a single-family house built between 2010 and 2015 in an ambitious state of refurbishment shows a higher potential for electricity cost savings as shown in Figure 5.

Table 2. Overview of the resulting nominal storage capacities of the selected single-family buildings with a net floor area of 160 m² and in dependence of the power shift capability of the additional storage model.

Building description			Nominal storage capacity $C^{vs}_{nominal}$ / kWh						
Building Type	Age class	State of refurbishment	Power shift capability t_δ						
			2 h	3 h	4 h	5 h	6 h	8 h	12 h
SFH	1919-1948	Existing state	5.54	6.38	6.58	6.41	6.05	5.14	3.59
		Standard	7.01	8.3	8.78	8.75	8.42	7.32	4.98
		Ambitious	4.97	7.45	9.93	12.41	11.65	9.99	6.55
	1958-1968	Existing state	6.04	7.05	7.36	7.25	6.92	6.01	4.37
		Standard	7.09	8.39	8.87	8.84	8.5	7.39	5.02
		Ambitious	4.55	6.83	9.11	11.39	13.66	10.7	6.97
	2010-2015	Existing state	6.64	9.96	9.48	9.43	9.04	7.81	5.24
		Standard	5.88	8.82	10.46	10.39	9.95	8.59	5.74
		Ambitious	3.62	5.43	7.25	9.06	10.87	14.45	9.22

Table 3. Overview of the resulting maximum additional charging/discharging heat flows of the selected single-family buildings with a net floor area of 160 m² and in dependence of the power shift capability of the additional storage model.

Building description			Additional max charging/discharging power $\dot{Q}^{vs}_{charge/discharge,max}$/kW						
Building Type	Age class	State of refurbishment	Power shift capability t_δ						
			2 h	3 h	4 h	5 h	6 h	8 h	12 h
SFH	1919-1948	Existing state	2.77	2.13	1.64	1.28	1.01	0.64	0.3
			2.77	2.13	1.64	1.28	1.01	0.64	0.3
		Standard	3.43	2.71	2.15	1.72	1.38	0.9	0.41
			3.51	2.77	2.2	1.75	1.4	0.92	0.41
		Ambitious	3.47	2.75	2.19	1.75	1.41	0.92	0.47
			2.48	2.48	2.48	2.48	1.94	1.25	0.55
	1958-1968	Existing state	3.02	2.35	1.84	1.45	1.15	0.75	0.36
			3.02	2.35	1.84	1.45	1.15	0.75	0.36
		Standard	3.4	2.68	2.13	1.7	1.37	0.89	0.41
			3.55	2.8	2.22	1.77	1.42	0.92	0.42
		Ambitious	3.45	2.74	2.18	1.74	1.4	0.92	0.41
			2.28	2.28	2.28	2.28	2.28	1.34	0.58
	2010-2015	Existing state	3.39	2.68	2.13	1.7	1.36	0.89	0.4
			3.32	3.32	2.37	1.86	1.51	0.98	0.44
		Standard	3.42	2.71	2.15	1.72	1.38	0.9	0.41
			2.94	2.94	2.51	2.1	1.66	1.07	0.48
		Ambitious	3.44	2.72	2.17	1.74	1.39	0.91	0.42
			1.81	1.81	1.81	1.81	1.81	1.81	0.77

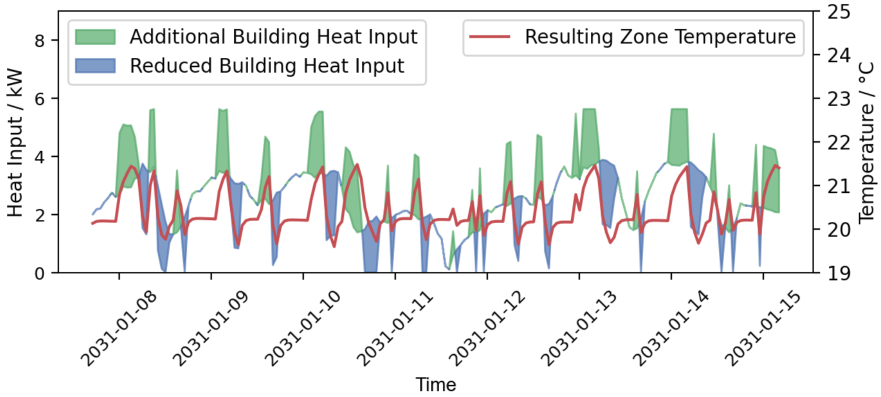

Figure 3. Optimized building heat input and resulting zone temperature in comparison with the heating demand at a constant zone temperature of 20 °C of a single-family household built between 1958 and 1968 in a standard state of renovation. The storage component of the building model is parameterized with a charging duration of 4 hours at full charging power.

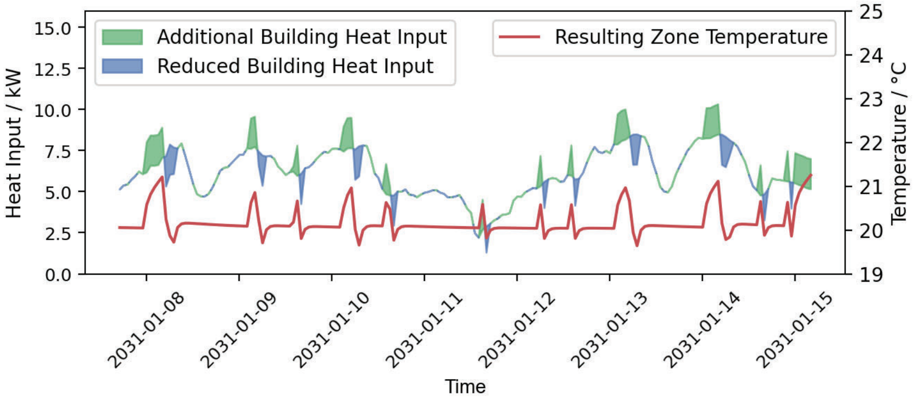

Figure 4. Optimized building heat input and resulting zone temperatures in comparison with the heating demand at a constant zone temperature of 20 °C of a single-family household built between 1958 and 1968 in the original state of renovation. The storage component of the building model is parameterized with a charging duration of 4 hours at full charging power.

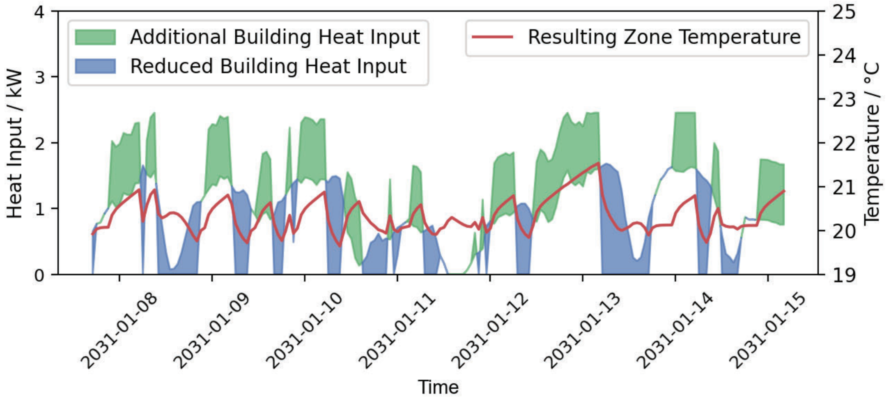

Figure 5. Optimized building heat input and resulting zone temperatures in comparison with the heating demand at a constant zone temperature of 20 °C of a single-family household built between 2010 and 2015 in an ambitious state of renovation. The storage component of the building model is parameterized with a charging duration of 8 hours at full charging power.

3.5. Flexibility quantification of individual buildings

The utilization of the flexibility potentials in the operation of the investigated buildings varies significantly with the building age class and the state of refurbishment. To quantify the flexibility potentials, the flexibility efficiencies and the annual electricity cost savings are calculated for all demand response events during the year. The results are presented in Table 4 and Table 5. The highest annual electricity cost savings of 131.45 € can be reached by the well-insulated building constructed between 2010 and 2015 in its original state, which corresponds to about 12.5% of its original annual electricity costs without utilizing the thermal flexibility. In general, most fairly well-insulated buildings show relatively high saving potentials. It is noteworthy, that the very well insulated buildings have less total electricity cost savings than the worse insulated buildings of the same class, due to the decrease in the total energy demand. The relative annual savings, compared to the costs for electricity without utilizing the thermal flexibility, increase with better insulation for all buildings. The highest utilization efficiencies of the virtual storage are reached by the buildings built between 1919 and 1948 and the building built between 1958 and 1968, both in an ambitious state of refurbishment. In the chosen environment, most buildings show the best efficiency with a power shift capability of 4 hours. Nevertheless, buildings with well-insulated envelopes show an optimal modelling approach using a power shift capability of 6 or 8 hours. Therefore, poorly-insulated buildings with high heat loss rates show higher potentials for short-term energy storage use while well-insulated buildings display higher potentials for longer energy storage durations.

Table 4. Overview of the annual electricity cost savings from the energy system optimization of a SFH with a net floor area of 160 m² and in dependence of the power shift capability of the additional storage model.

Building description			Annual electricity cost savings						
Building Type	Age class	State of refurbishment	Power shift capability t_δ						
			2 h	3 h	4 h	5 h	6 h	8 h	12 h
SFH	1919-1948	Existing state	49.94 € 0.90%	52.50 € 1.00%	45.98 € 0.80%	36.37 € 0.70%	27.36 € 0.50%	15.52 € 0.30%	5.97 € 0.01%
		Standard	102.35 € 6.60%	116.30 € 7.50%	111.75 € 7.20%	98.21 € 6.30%	81.68 € 5.30%	52.14 € 3.40%	18.41 € 1.20%
		Ambitious	61.33 € 9.20%	87.75 € 13.20%	105.41 € 15.90%	114.65 € 17.30%	102.37 € 15.50%	73.17 € 11.00%	29.02 € 4.40%
	1958-1968	Existing state	67.41 € 1.80%	74.66 € 2.00%	68.28 € 1.90%	56.70 € 1.60%	44.97 € 1.20%	26.08 € 0.70%	9.67 € 0.30%
		Standard	102.38 € 7.50%	116.35 € 8.60%	112.46 € 8.30%	99.45 € 7.30%	83.25 € 6.10%	53.52 € 3.90%	19.34 € 1.40%
		Ambitious	54.54 € 9.30%	78.27 € 13.40%	94.50 € 16.20%	103.83 € 17.80%	106.35 € 18.20%	75.41 € 12.90%	30.85 € 5.30%
	2010-2015	Existing state	93.78 € 8.90%	131.45 € 12.50%	119.76 € 11.40%	108.28 € 10.30%	92.30 € 8.80%	60.69 € 5.80%	22.38 € 2.10%
		Standard	79.94 € 8.90%	113.40 € 12.70%	123.87 € 13.90%	114.50 € 12.80%	99.46 € 11.10%	67.23 € 7.50%	25.57 € 2.90%
		Ambitious	40.39 € 9.10%	58.60 € 13.20%	72.14 € 16.30%	80.89 € 18.20%	84.23 € 19.10%	82.23 € 18.50%	38.71 € 8.70%

Table 5. Overview of the demand response efficiencies from the energy system optimization of a SFH with a net floor area of 160 m² and in dependence of the power shift capability of the additional storage model.

Building description			Utilization efficiency of virtual storage η_e / -						
Building Type	Age class	State of refurbishment	Power shift capability t_δ						
			2 h	3 h	4 h	5 h	6 h	8 h	12 h
SFH	1919-1948	Existing state	0.4931	0.486	0.4481	0.4128	0.391	0.32	0.1925
		Standard	0.7592	0.7631	0.753	0.7395	0.7124	0.6738	0.5706
		Ambitious	0.7268	0.7628	0.7758	0.7861	0.7806	0.7609	0.6927
	1958-1968	Existing state	0.6382	0.6255	0.6034	0.5738	0.5384	0.4906	0.3788
		Standard	0.7644	0.7709	0.7644	0.751	0.7329	0.69	0.5896
		Ambitious	0.7177	0.752	0.7658	0.777	0.7837	0.7642	0.7077
	2010-2015	Existing state	0.7607	0.7885	0.7815	0.7737	0.7622	0.7264	0.6372
		Standard	0.7491	0.7782	0.7879	0.7834	0.7762	0.7453	0.6711
		Ambitious	0.6942	0.7282	0.7458	0.7549	0.763	0.7729	0.7513

4. Discussion

In the present work, a modelling approach considering the thermal flexibility of buildings is presented and the flexibility potentials of a selection of representative buildings is quantified. It is shown that the presented building model can be integrated in an energy system optimization framework, in order to help utilizing the flexibility potentials of the individual buildings as well as a building group, district or district heating network. The building model approach used to simulate the buildings takes into account the heat transfer and storage characteristics using five nodes for each opaque building element. However, this approach is still a simplification and the real heat transfer mechanisms may differ from the results in this work. The linear representation of the buildings storage characteristics in the energy system optimisation only accounts for parts of the real flexibility potential and a non-linear representation could lead to better performances of the buildings. In addition, more detailed analyses to quantify the storage parameters are necessary and broader test environments must be implemented to improve the robustness of the models. Nevertheless, the representation of a building using a generic sink and a generic storage component allows the integration in most optimization frameworks and the application in diverse planning processes of different stakeholders, while still allowing to take into account more detailed heating demand analyses. The approach is validated by integrating the optimized heat input in the building simulation model and testing the resulting room temperature to ensure that the specified limits are not exceeded. It is shown that utilizing thermal flexibilities can lead to annual cost reductions in the energy import of up to 130 € for a single-family house built between 2010 and 2015 with a net floor area of 160 m². For the application of the building models and the quantification of their flexibility in a district energy system or district heating systems, the best performing flexible building models can be chosen and integrated in an optimization model. The best storage model approaches for optimizing the buildings operation depend on the building type and the state of refurbishment. While well-insulated buildings indicate a more economically efficient utilization with longer storage durations and lower charging and discharging heating powers, poorly and moderately insulated buildings show higher potentials in the short-term utilization of their flexibility. Therefore, different building types should also be utilized accordingly. A modern district with 100 buildings built between 2010 and 2015 in a standard state of refurbishment could lead to annual electricity cost reductions of up to 12 300 € if the flexibility potential is utilized. The available storage capacity for this district is up to 1 046 kWh and the possible power shift is 215 kW for the charging event and 251 kW for the discharging event. The annual electricity cost reductions linked to the renovation from the original state to the standard state of renovation without the exploitation of the flexibility are 15 552 €, without including taxes and other fees in the calculation. An exemplary district with 100 SFH, equally distributed in both non-refurbished and standard refurbished condition, can achieve annual electricity cost savings of up 9 550 €, when the flexibility is utilized and provide 772 kWh of virtual storage capacity and 250 kW or 224 kW of power shift during the charging or discharging event. If additional renewable energy from own generation plants, such as photovoltaic systems, can be integrated into the energy system, the savings from exploiting flexibility can be further improved. Investigating the impact of these systems will be part of future studies.

In addition to the findings off the present work, the consideration of thermal flexibilities in the energy system design optimization could lead to savings in the investment costs and identifying efficient and cost-effective operation strategies. The optimization of the energy system can take into account the availability of waste heat, the fluctuating efficiency of heat generation units and the conditions of available heat sources. Utilizing the thermal flexibility of buildings can therefore benefit the integration of local renewable energy sources like wind energy, solar power or waste heat, especially when exploited on a district level. However, since individual households do not have excess to the day-ahead electricity market, the buildings flexibility is most likely to be utilized on a district level or a district heating network. Therefore, new pricing-models for heat must be developed. Yet, in district energy systems and district heating networks, the drawback often lies in the metering devices or the operational control of the buildings. Hence, multi-family buildings might be more likely to be considered to provide flexibility, and therefore the quantification of flexibility should be extended to more building types.

5. Conclusion

The transformation of the heating sector in buildings will face the challenge of integrating fluctuating renewable energy sources to become sustainable. To adjust the heating demand to the volatile generation of renewable energies, it is necessary to use comprehensive methods and tools to quantify the flexibility of the buildings and to incorporate this potential into the diverse planning processes of integrated energy systems, particularly on a district level and for district heating networks. By characterizing the heat transfer dynamics of a selection of buildings with a simulation based on the DIN EN ISO 52016, a generic approach is used to model the building demands and flexibility properties in an energy system optimization framework. By following this procedure, building flexibility indicators can be quantified and appropriate utilization strategies can be identified for individual buildings, building groups, or districts in a variety of applications. Based on a variable day-ahead electricity price and a realistic heat pump coefficient of performance, it is shown how the flexibility of single-family houses can be exploited to reduce energy costs. Depending on the building type and the state of insulation, there are different opportunities for exploitation. When only linear modelling approaches are used, well-insulated buildings tend to be more cost-effective by gradually increasing the heating input and storing the energy for a longer period, while poorly insulated buildings tend to perform better with shorter storage durations and higher charging powers. Still, all investigated buildings show the possibility of cost reductions when utilized and can play an important role in an integrated energy system. Future research should expand the flexibility analysis to include a wider variety of building types and groups. Multi-family buildings, larger apartment blocks, and commercial buildings, in particular, may exhibit different energy flexibility potential and could also play distinct roles in integrating renewable energy into the energy system. Furthermore, energy storage capabilities of district heating networks could be assessed in a similar way and help finding operation strategies or identify optimal supply and return line temperature profiles. In addition to the building analysis, deeper understanding of the flexibility in the operation of the heat generation units and heating emitter systems is necessary. Utilizing flexibilities promises to play an important role in an integrated energy system, especially when exploited on a district level. Until now, the heat generation of large-scale heat pumps in district energy systems mostly covers the base load operation. Nevertheless, the flexible operation of heat generation plants is crucial to leverage variable electricity prices and cope with fluctuating renewable energy sources.

References

[1] Europäische Kommission. The European Green Deal.

[2] Arbeitsgemeinschaft Energiebilanzen e.V. Anwendungsbilanzen zur Energiebilanz Deutschland: Endenergieverbrauch nach Energieträgern und Anwendungszwecken; AGEB Anwendungsbilanzen: Arbeitsgemeinschaft Energiebilanzen e.V.; 2019.

https://doi.org/10.52202/069564-0310

[3] Umweltbundesamt: Umwelt Bundesamt. Energieverbrauch für fossile und erneuerbare Wärme. Available at: <https://www.umweltbundesamt.de/daten/energie/energieverbrauch-fuer-fossile-erneuerbare-waerme#warmeverbrauch-und-erzeugung-nach-sektoren> [accessed 01.04.2021]
[4] Bundesministerium für Wirtschaft und Energie. Energiedaten: Gesamtausgabe. Berlin; 2021.
[5] Sensfuß F, Lux B, Bernath C*, et al.* Langfristszenarien für die Transformation des Energiesystems in Deutschland 3. Kurzbericht: 3 Hauptszenarien. Karlsruhe: Fraunhofer ISI, Karlsruhe; 2021.
[6] Jensen SØ, Marszal-Pomianowska A, Lollini R*, et al.* IEA EBC Annex 67 Energy Flexible Buildings. Energy and Buildings 2017; 155: 25–34.
[7] Junker RG, Azar AG, Lopes RA*, et al.* Characterizing the energy flexibility of buildings and districts. Applied Energy 2018; 225: 175–82.
[8] Guelpa E, Verda V. Demand response and other demand side management techniques for district heating: A review. Energy 2021; 219: 119440.
[9] Kathirgamanathan A, Péan T, Zhang K*, et al.* Towards standardising market-independent indicators for quantifying energy flexibility in buildings. Energy and Buildings 2020; 220: 110027.
[10] Reynders G, Amaral Lopes R, Marszal-Pomianowska A, Aelenei D, Martins J, Saelens D. Energy flexible buildings: An evaluation of definitions and quantification methodologies applied to thermal storage. Energy and Buildings 2018; 166: 372–90.
[11] Reynders G, Diriken J, Saelens D. Generic characterization method for energy flexibility: Applied to structural thermal storage in residential buildings. Applied Energy 2017; 198: 192–202.
[12] Kun Zhang, Michaël Kummert, editors. Potential of building thermal mass for energy flexibility in residential buildings : a sensitivity analysis; 2018.
[13] Kathirgamanathan A, Murphy K, Rosa M de, Mangina E, Finn D, editors. Aggregation of Energy Flexibility of Commercial Buildings; 2018.
[14] Péan T, Torres B, Salom J, Ortiz J, editors. Representation of daily profiles of building energy flexibility; 2018.
[15] Vandermeulen A, Reynders G, van der Heijde B*, et al., editors.* Sources of Energy Flexibility in District Heating Networks: Building Thermal Inertia Versus Thermal Energy Storage in the Network Pipes; 2018.
[16] Protopapadaki C, Reynders G, Saelens D. Bottom-up modelling of the Belgian residential building stock: impact of building stock descriptions. Proceedings of the 9th International Conference on System Simulation in Buildings - SSB2014; 2014.
[17] Deutsches Institut für Normung e.V. DIN EN ISO 52016-1 Energetische Bewertung von Gebaeuden – Energiebedarf für Heizung und Kühlung, Innentemperaturen sowie fühlbare und latente Heizlasten – Teil 1: Berechnungsverfahren (ISO 52016-1:2017); 2018 2018.
[18] Le Dréau J, Heiselberg P. Energy flexibility of residential buildings using short term heat storage in the thermal mass. Energy 2016; 111: 991–1002.
[19] EnergyPlus Documentation - Input Output Reference; 2022 [accessed 20.12.2022] Available at: <https://energyplus.net/assets/nrel_custom/pdfs/pdfs_v22.2.0/InputOutputReference.pdf>.
[20] Yang X, Pan L, Guan W, Ma H, Zhang C. Heat flexibility evaluation and multi-objective optimized control of a low-energy building with district heating. Energy and Buildings 2022; 277: 112523.
[21] Gils HC. Balancing of intermittent renewable power generation by demand response and thermal energy storage 2015.
[22] Zerrahn A, Schill W-P. On the representation of demand-side management in power system models. Energy 2015; 84: 840–5.
[23] Krien U, Schönfeldt P, Launer J, Hilpert S, Kaldemeyer C, Pleßmann G. oemof.solph—A model generator for linear and mixed-integer linear optimisation of energy systems. Software Impacts 2020; 6: 100028.
[24] Kotzur L. Future grid load of the residential building sector. Dissertation.
[25] Schütz T, Schiffer L, Harb H, Fuchs M, Müller D. Optimal design of energy conversion units and envelopes for residential building retrofits using a comprehensive MILP model. Applied Energy 2017; 185: 1–15.
[26] Bacher P, Madsen H. Identifying suitable models for the heat dynamics of buildings. Energy and Buildings 2011; 43(7): 1511–22.
[27] IWU Institut Wohnen und Umwelt. TABULA Calculation Method: Energy Use for Heating and Domestic Hot Water; Reference Calculation and Adaptation to the Typical Level of Measured Consumption; 2013.
[28] Institut Wohnen und Umwelt. Deutsche Wohngebäudetypologie: Beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden; 2. erw. Aufl. Darmstadt: IWU 2015.
[29] Deutscher Wetterdienst (DWD), Bundesamt für Bauwesen und Raumordnung (BBR). Ortsgenaue Testreferenzjahre von Deutschland für mittlere, extreme und zukünftige Witterungsverhältnisse; Handbuch; 2017.
[30] Jesper M, Schlosser F, Pag F, Walmsley TG, Schmitt B, Vajen K. Large-scale heat pumps: Uptake and performance modelling of market-available devices. Renewable and Sustainable Energy Reviews 2021; 137: 110646.