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Integration of a Europe-wide public building database with retrofit strategies and a thermal inertia model into an open-source optimization framework

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Abstract. The building sector currently accounts for 40 % of global energy consumption and one third of total greenhouse gas emissions, with a significant portion allocated to thermal energy supply. Achieving global climate goals requires the transition to renewables in energy supply systems. The cost efficiency first principle suggests that improving energy efficiency is a key measure on that way, which includes building envelope retrofits. Open-Source tools for optimization of building energy systems exist, e.g. the open energy system framework (oemof), a tool equipped with a comprehensive library of generic components that empowers energy system modeling and optimization. However, these tools typically lack the linkage between retrofit strategies and energy system optimization, do not consider the thermal inertia of the building in the operational optimization and require extensive input data. In this contribution, we present a new open-source feature of oemof that combines the 5RC thermal building model (based on ISO 13790) with the TABULA building database and makes them available for optimization workflows. This enables oemof to optimize the energy system design and operation, including the thermal inertia and controlling the indoor temperature within a comfort zone. The optimization is performed for three residential building retrofit states in hourly time steps with a mixed-integer linear programming (MILP) approach. The chosen approach works with little input data for 20 European countries and allows the optimization of a wide range of residential buildings for three retrofit states. A case study demonstrates the applicability of the new method.

1. Introduction

Against the backdrop of advancing anthropogenic climate change [1], the transformation of the energy system is one of the key challenges of the 21st century [2]. Among the contributors to greenhouse gas emissions, the building sector stands prominent with a third of total global emissions, particularly in its thermal energy supply [3].

This requires a major structural change in the heating sector at building level. On the one hand, efficiency measures such as building retrofit will lead to a reduction in heat demand, while on the other hand key technologies based on renewable electricity, such as heat pumps, must be used [4; 5].

The amortization time of retrofits is determined by the energy saving potential, the climatic boundary conditions, the indoor target temperature and the financial framework conditions, such as retrofit costs and energy prices [6]. In the future, the costs of retrofit will rise and if the investor does not benefit financially from this in the long term, there will be no retrofits to increase energy efficiency. Commercial dynamic simulation tools, such as EnergyPlus [7] and TRNSYS [8], leverage complex nonlinear building physics. While powerful, they necessitate extensive input data, entail relatively long computation times, and are highly constrained by usage limitations in their free demo versions. Various open-source software tools, specialized in distinct aspects of optimizing building energy systems, exist, such as the Open Energy System Framework (oemof). However, these tools typically fall short by not simultaneously addressing these three following points [9]:

(i) Lacking the linkage between retrofit strategies and energy system optimization
(ii) Neglecting consideration of thermal inertia in buildings, thereby failing to operationally optimize the internal temperature within a comfort zone
(iii) Requiring extensive input data

In response to these gaps, this paper presents a novel workflow that bridges the gap between retrofit strategies as well as internal temperature and energy system optimization. This approach involves the generation of a 5RC thermal building model using the comprehensive TABULA building database, integrated into oemof. The TABULA database encompasses typologies for residential buildings across 20 European countries, categorizing buildings based on size, age, type, and three distinct retrofit states, offering essential building physical parameters. oemof, a versatile open-source tool equipped with a comprehensive library of generic components, enables energy system modeling as well as designing and operational optimization, striving towards cost reduction and minimizing CO_2 emissions. The 5RC model, rooted in the ISO 13790 standard, represents a thermal resistor-capacitor network with hourly resolution, reflecting thermal storage capacity through capacitance and thermal losses via resistances.

The integration of TABULA and the 5RC model into oemof simplifies the operational optimization of building energy use with internal temperature regulation, within a comfort zone, and comparing three retrofit strategies per building. This incorporation expands the capabilities of an already open-source, extensively tested, and user-friendly framework and therefore, contributes to the drive for enhanced cost-optimal energy efficiency within the building environment. The implemented workflow is applied to a single-family house in Germany with its energy system. The developed `thermal-building-model` package, created specifically for this research as part of the `oemof` tree, can be found in the associated GitHub repository: `https://github.com/oemof/thermal-building-model`.

The paper is structured as follows: The novel methodology is explained in Section 2. For this, the theoretical background is introduced and the integrated workflow in oemof presented. In Section 3, the methodology is applied and validated by optimizing the annual energy costs of a single family household in Germany. Finally, Section 4 summarizes the conclusion of this work.

2. Methodology

This Section explains the workflow integrated in omeof and the theoretical foundations required for this. Therefore, we first introduce oemof in Subsection 2.1. In Subsection 2.2 the thermal building model in the form of a 5RC model is explained. Afterwards, in Subsection , the building data base with its building typology is shown. In Subsection , based on the previously defined theory, the implemented workflow into oemof is explained and illustrated.

2.1. Open energy modelling framework (oemof)

The open energy modelling framework (oemof) models energy systems, based on a graph structure consisting of nodes connected by directed edges, which represent the flow of energy carriers and resources, as well as their conversion and consumption. Specifically, nodes are divided into buses and components. Components represent actual producers, consumers or any processes of the energy system, while buses represent how this components interconnect. Meanwhile, edges represent inputs and outputs as flows of a component. The resulting graph generated by oemof contains the previously described [10]. The oemof.solph [11] package, as part of oemof, converts this graph into an optimisation problem [12].

The conversion relies on the optimisation package Pyomo in the programming language Python [13]. Afterwards, the model is passed to an external solver that minimizes the costs. These costs are allocated to buses or components and can be economic, environmental, technical, or any kind of cost selected by the user [12]. Due to the object-oriented graph based data model, modelling an energy systems does not require deep knowledge about mathematical optimization or an algebraic modelling language to implement linear (LP) and mixed-integer linear (MILP) problems. Therefore, only comprehensive domain-specific knowledge (here: about energy systems) is of need [12].

2.2. Thermal building model based on a 5RC electrical scheme

The thermal behavior of buildings can be simulated with different methods. A popular approach to create dynamic models, often called resistance-capacitance (RC) models, is based on the similarity between flow of electric current and heat flux. It includes resistance and capacitance elements as well as voltage and current sources [14]. In ISO 13790 [15], several calculations methodologies for heating and cooling demand are presented. The 5RC model is a simplification of a dynamic simulation with the aim of the same degree of transparency, comparative precision, and robustness, as well as [15]:

- a clearly defined, bounded set of equations that allows traceability of the computational process,
- a reduction of input data to a minimum,
- unambiguous procedures of the calculation.

The norm represents a full description of the hourly method based on five resistances and one capacitance (5RC) in form of a network model for a zone (see Figure 1). A building can be represented by a single zone or multiple zones. For this, the capacitance serves as the thermal storage capacity of the building, while resistances represent thermal interactions with the environment. To streamline calculations and reduce computational complexity, it simplifies the representation of thermal capacity in a single capacitor element. The model represents heat exchange between interior and exterior surfaces through five thermal resistance elements connected to three internal nodes. These nodes represent the temperature of the wall surfaces (T_{s}), the temperature of the effective thermal mass (T_{m}), and the indoor air temperature (T_{air}). Moreover, the model includes two external nodes, which correspond to the outdoor temperature (T_{e}) and the ventilation temperature (T_{sup}). The heating or cooling flow (F_{HC}) is supplied to or extracted from the indoor air node (T_{i}). The heat flows resulting from internal heat gains (F_{int}) and solar heat gains (F_{sol}) are connected to the indoor air temperature (T_{i}), the internal environment temperature (T_{s}), and the thermal mass temperature (T_{m}). The heat transfer through ventilation (H_{ve}) is modeled between the supply air temperature (T_{sup}) and the internal air temperature (T_{i})). The heat transfer coefficient for all opaque components, such as exterior walls, the roof, and the ground floor ($H_{\mathrm{tr,op}}$), is split into external ($H_{\mathrm{tr,em}}$) and internal parts ($H_{\mathrm{tr,ms}}$). It is connected to the single thermal capacity (C_{m}) with the corresponding surface area of all lumped elements (A_{m}). The heat transfer coefficient ($H_{\mathrm{tr,is}}$) is a coupling resistance

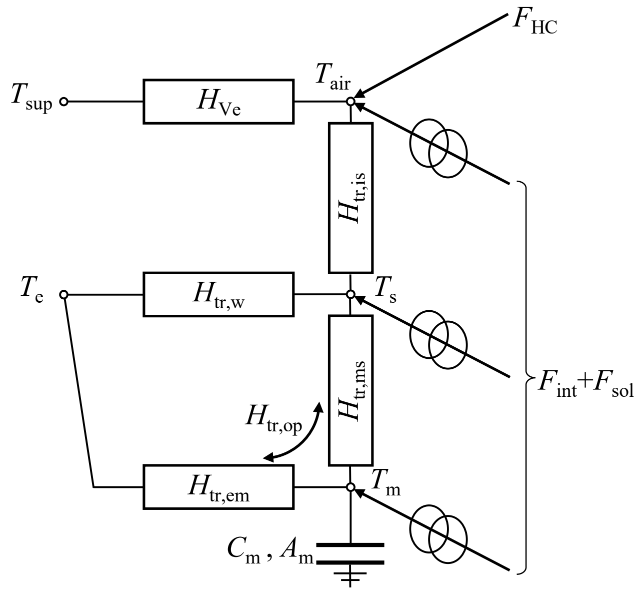

Figure 1. Electrical scheme of the 5RC building model

to connect T_i and T_e. For a detailed explanation of the calculation of the resistances and the capacitance as well as the physics and the equations of the model, we refer either to ISO 13790 [15], to Brune et. al [16] or to Michalak [14].

2.3. European projects TABULA and EPISCOPE

Building archetypes and the generation of regional or national typologies have been an important research topic for several years. During the projects TABULA (2009–2012) and EPISCOPE (2013–2016), experiences were summarized internationally and a European standardized framework for residential building typologies was developed. A building typology defined in the project refers to a description of the criteria for the definition of typical buildings as well as the set of building types itself [17]. It was applied to 20 European countries [18]. The concept of building typology focuses on building parameters related to energy consumption. In total, the building typology is classified by these three specific parameters: [17; 19]

- **Locations** are linked to climatic areas of a nation. Therefore, several national building typologies can exist with different typical building features, as e.g. construction principles.
- **Construction periods** are linked to constructive materials and principles. These constructions periods are defined for countries separately, according to changes in building practice and regulations, linked e.g. to energy efficiency legislation.
- Regarding **building size and shape**, the project considers single-family houses, terraced houses, multi-family houses, apartment blocks, and several subtypes of these.

On that basis, researchers developed a national building typology for each participating country as a set of model reference buildings, each of them with its specific energy-related properties [17]. This framework enables the estimation of energy demands in residential building stocks at the national level. Furthermore, it facilitates the prediction of the potential effects of energy efficiency measures and the identification of effective strategies for enhancing the energy performance of existing buildings [17; 18].

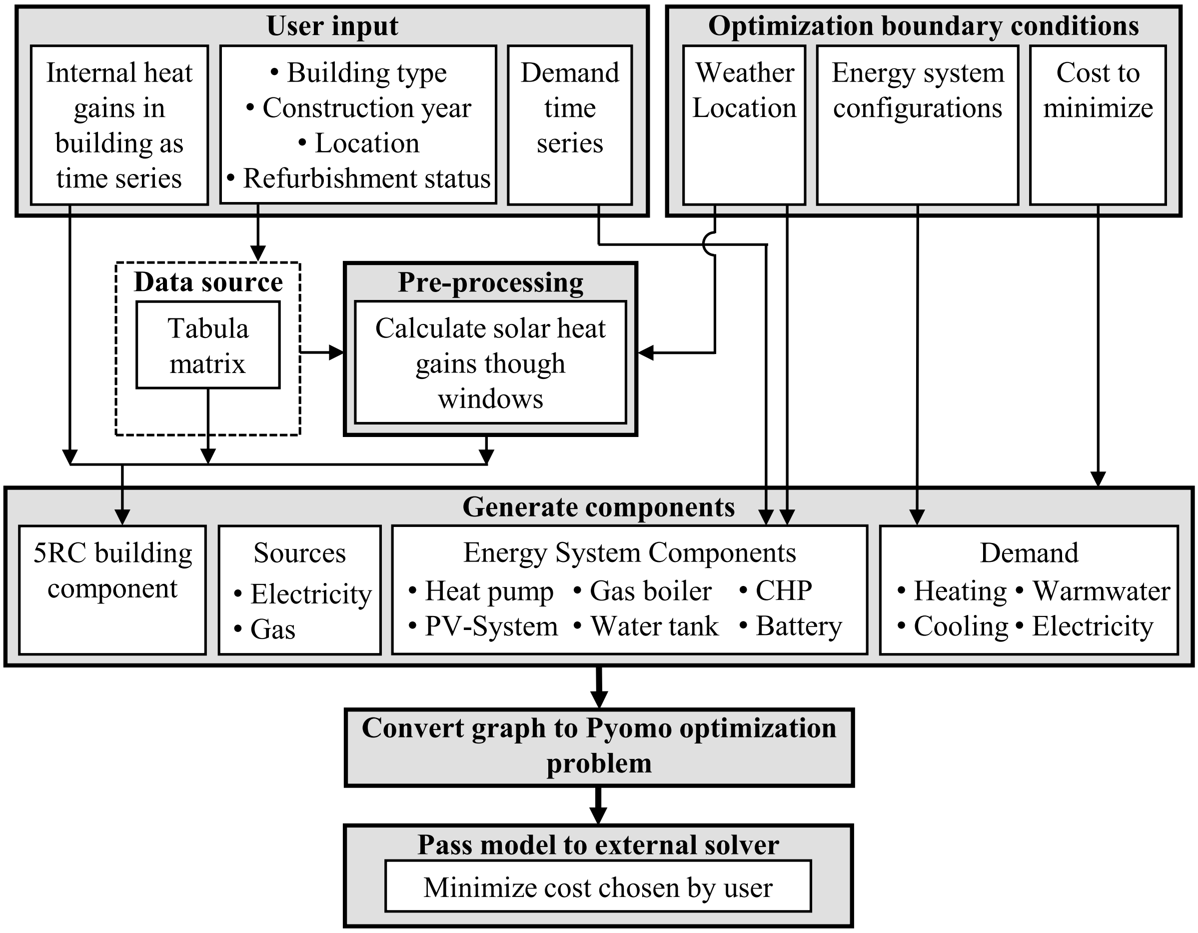

Figure 2. Workflow of optimization in oemof.solph with the 5RC building model

Moreover, the project team developed an approach to calculate the heat demand for the common building typology structure. It includes a standards reference calculation procedure based on CEN standards, by using an equivalent data structure for each building [20]. For this purpose, an easy-to-use and comprehensible web tool application got developed, the TABULA web tool [21]. In addition a database for all buildings is published in the form of an excel workbook, which provides the same methodology for calculating the heat demand as the web tool [22].

2.4. Integration of models into oemof

Figure 2 illustrates the holistic optimization workflow for residential buildings linked to the TABULA database within oemof. The mandatory user input concerning the building involves defining the building type, construction year class, location, and retrofit status. For this, the understanding of location in relation to the definition of TABULA building typologies is expanded by the nation itself. These inputs generate a unique building code used to access specific parameters stored in the database mentioned in Subsection 2.3.

In the TABULA database, a matrix of relevant parameters (such as U-values, building dimensions, etc.) is cataloged for every building and can be retrieved based on the unique building code. While 15 EPW weather files for cities in Germany are provided within oemof, additional EPW weather files can be accessed from the repository of free climate data for building performance simulations [23]. In addition different weather formats can be used. The internal gains compromise heat gains from occupancy, lighting, and machinery and needs to be provided by the user. Guidelines, standard profiles or software-supported solutions can be used for this purpose.

The energy system configurations includes selecting components, parameterizing (e.g. setting loss values, minimum and maximum boundaries for nominal capacities for optimization), and specifying variable costs for flows (e.g. electricity price), fixed costs (e.g. maintenance costs), and necessary investments for technical components (e.g. price per nominal capacity). The costs can either be environmental, economic, or technical.

Subsequently, components are generated based on the user input. We particularly emphasize the 5RC building component, a recent addition to oemof. Details on other components can be found in the oemof.solph documentation [24]. The 5RC building component is represented as a single network node, featuring input flows for heating and output flows for cooling. It requires the initialization of set temperatures for heating and cooling. They act as boundary conditions for optimizing the internal temperature of the building. Additionally, generating the 5RC building component necessitates considering internal heat gains, pre-calculated solar heat gains, and specific building parameters extracted from the TABULA Excel sheet.

Finally, the generated components of the the energy system model are converted from oemof to a Pyomo optimization problem. This problem is handed over to an external solver to minimize the cost type chosen by the user. It includes the design and operation optimization of the building energy systems and therefore the regulation of the internal temperature of the building, by considering the thermal inerita of the building. The optimization process can be executed for any retrofit status, which provides a basis for decision-making.

3. Case study

To validate the implemented workflow, this Section focuses on calculating the costs for three TABULA retrofit scenarios applied to a single-family household. The Section is divided into three Subsections: Subsection 3.1 describes the investigated building, retrofit strategies, and technologies, Subsection 3.2 provides the economic basis of calculation, while Subsection 3.3 presents the results.

3.1. Description of the investigated building and boundary conditions

The examined structure is a single-family household built between 1958 and 1968 in Berlin, Germany, with a reference floor area of $159\,\mathrm{m}^2$. The primary focus of the TABULA retrofit scenarios involves additional insulation on exterior walls, the roof, and the ground floor as well as new windows. The relative full costs in €/m^2 can be expressed as function of the equivalent insulation thickness in m (see Table A1). These relative full costs encompass both material and labor expenses, constituting the comprehensive full costs. For the investigated building, this results in the total costs detailed in Table A2. In addition to this, the profiles for the electricity demand and domestic hot water demand for a household of two married working adults and three children are generated by the LoadProfileGenerator. The internal heat gains attributed to lighting and electronic devices are derived from the LoadProfileGenerator, while internal heat gains of humans are neglected for simplification [25].

It is also assumed that no functioning heating energy system is available, so that an investment is required. The set point temperature for the heating system is 20 °C. Beyond this, no set point temperature for cooling is specified, following the common assumption for residential buildings in Germany, that the amount of time with overheating in summer is moderate and acceptable and no cooling equipment needs to be installed. Investigated technologies include a heat pump, a gas heater, a heat storage and a photovoltaic system. The technological and economical parameters of these technologies are detailed in Table A3 and Table A4 respectively. The

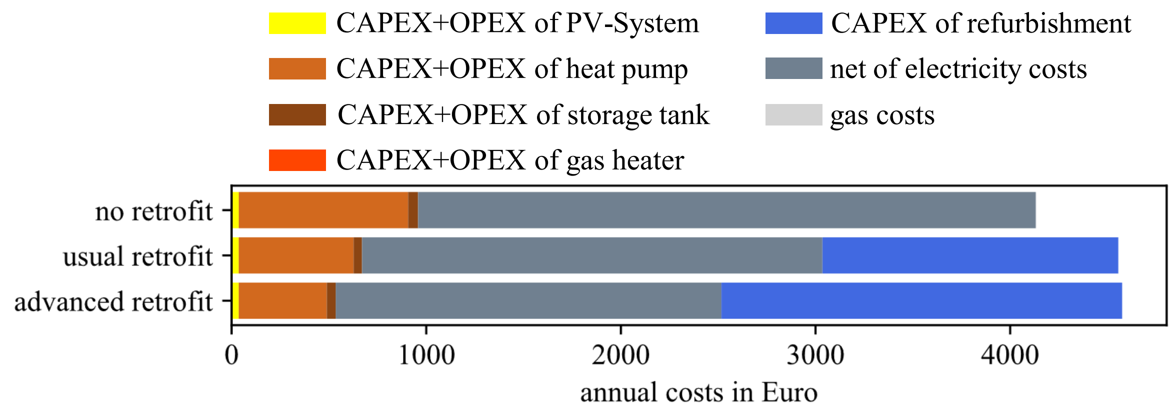

Figure 3. Annual energy costs for a single family house in Germany

maximum investigated power of the heat pump and gas heater is constrained to the maximum thermal load throughout the year. Furthermore, the assumed electricity, gas and feed-in price, their percentage increase in the future, as well as the imputed interest rate are shown in Table A5. While a brief overview of these parameters is provided, it's important to note that our primary focus in this article lies on detailing the applied methodology rather than an exhaustive examination of these parameters.

3.2. Economic calculation

For comparison of the three retrofit scenarios the *annual energy costs* are calculated using equation (1). For this purpose each component (i) undergoes calculation of the capital expenditure ($CAPEX_i$) with the weighted average cost of capital ($WACC_i$) and the operational expenditure ($OPEX_i$). The observation period (t) spans 20 years. Therefore, if a component has a longer lifetime, a linearly depreciated residual value (rv_i) is included. Furthermore, electricity, gas and feed-in prices are considered with an annual percentage increase.

$$annual\ energy\ costs = \sum_i CAPEX_i \cdot WACC + OPEX_i - \frac{rv_i}{t} \tag{1}$$

3.3. Results

In Figure 3 we present the results concerning annual energy costs. For this, the figure aggregates the *CAPEX* and *OPEX* for each component as well as the net electricity costs resulting from electricity consumption costs minus feed-in remunerations. In particular, it can be observed that an improvement in the retrofit status leads to a lower delta in net of electricity costs and investments costs in heating technologies. This can be attributed to the decreased heat demand. However, it is important to highlight that, firstly, despite the operational cost and technology investment savings, the overall investments in retrofit for each strategy exceed the accrued savings. Secondly, the results are highly dependent on the chosen framework conditions and differ slightly for each retrofit strategy. Thirdly, no maintenance costs for the building are taken into account for simplification, although these costs would probably be higher for a non-retrofitted building than for a retrofitted building. The model generation, optimization, and result saving processes were completed within a remarkable time frame of under 10 seconds per building. These computations were executed on a computing platform powered by an 11th Gen Intel(R) Core(TM) i7-1185G7 processor running at 3.00 GHz (with a base frequency of 1.80 GHz) and equipped with 16.0 GB of RAM.

4. Conclusion

This paper introduces an innovative and practical workflow, implemented in an open source software, that integrates retrofit strategies, internal temperature regulation, and energy system optimization. The proposed workflow creates a synergy between the TABULA building database, the 5RC thermal building model, and the Open Energy Modelling Framework (oemof), addressing existing gaps in open-source software tools. By combining these elements, the paper streamlines the operational and design optimization of building energy system and allowing for the comparison of three retrofit strategies per building.

The case study, applied to a single-family house in Germany, demonstrates the practical application of the implemented workflow. The economic calculation, considering capital and operational expenditures over a 20-year period, reveals insights into the cost-effectiveness of different retrofit strategies. The results presented in Figure 3 highlight the trade-offs between cost savings and the investments required for retrofit. It is noteworthy that despite the observed savings in operational cost and investment in heating technologies, the overall investments in retrofit for each strategy surpass the accrued savings. This can be due to a variety of reasons. Firstly, the calculation assumes that retrofit investments have a limited lifetime, while no future costs are considered for the status quo, despite expected expenses for maintenance. Secondly, the results are highly depended to the chosen framework conditions.

In conclusion, this paper contributes to the field by providing a comprehensive workflow for optimizing residential building energy systems. By bridging the gap between retrofit strategies, internal temperature regulation, and energy system optimization, the proposed approach offers a valuable tool for researchers, practitioners, and policymakers striving for enhanced energy efficiency in the building environment. Future work could focus on expanding the application of this workflow to diverse building types, including retrofit of building parts into the design optimization process, further advancing its practical utility by automatically connecting the LoadProfileGenerator and deposit a database for costs of technologies and retrofit strategies.

Appendix

Table A1. Relative full cost for the retrofit of the investigated building

Part of the building	y = cost in €/m^2 x = additional thickness in m	Lifetime	Source
Exterior wall	$y = 243.1 \cdot x + 87.35$	50 a	[26]
Roof	$y = 270.2 \cdot x + 172.82$	50 a	[26; 27]
Floor	$y = 104.1 \cdot x + 26.506$	50 a	[26; 27]
Window	$y = 1205.4 \cdot x - 0.0013$	50 a	[26–29] own calculation

Table A2. Total cost for the retrofit of the investigated building

Part of the building	Total area	Additional insulation thickness		Cost	
		standard	advanced	standard	advanced
Exterior wall	149.9 m^2	0.12 m	0.24 m	17 466.6 €	21 839.5 €
Roof	168.9 m^2	0.12 m	0.30 m	34 665.7 €	42 880.3 €
Floor	115.8 m^2	0.08 m	0.12 m	4033.3 €	4515.3 €
Window	27.1 m^2	0.45 m	0.82 m	14 699.5 €	26 786.0 €
All parts				70 865.1 €	96 021.1 €

Table A3. Technological parameters for the investigated heating technologies

Technology	Efficiency factor	Max. value	Source
Heat pump	Dynamic COP from 10 °C to 35 °C is 4.5.	thermal demand	[30]
Gas heater	96 %.	thermal demand	[30]
Heat storage	charging with 99 %	4 m^3	[30]
	discharging with 99 %		[30]
	self-discharge of 6 %/h		[30]
Photovoltaic	84.03 %	10 kW_{peak}	[31]

Table A4. Economic parameters for the investigated heating technologies

Technology	CAPEX fixed	CAPEX specific	OPEX in % CAPEX per a	Lifetime	Source
Heat pump	5000 €	600 €/kW_{th}	2.0	20 a	[30]
Gas heater	2800 €	100 €/kW_{th}	1.5	20 a	[30]
Heat storage	800 €	1200 €/m^3	0.0	25 a	[30]
Photovoltaic	600 €	800 €/kW_{peak}	2.0	25 a	[30; 32]

Table A5. Economic parameters of general conditions

Parameter	Value	Annual increase	Source
Electricity price	0.274 €/(kW h)	1 %	[33], assumption
Gas price	0.1225 €/(kW h)	1 %	[33], assumption
Feed-in tariff	0.086 €/(kW h)	1 %	[34], assumption
Imputed interest rate	5 %	0 %	assumption

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