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Optimal Design of Building Energy Systems for Residential Buildings

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Abstract

This paper addresses the design and sizing of building energy systems for residential applications with exact optimization methods. Similar studies often rely on large simplifications, such as scaling the nominal outputs of representative heat pumps, boilers, combined heat and power units and electrical heaters. In contrast, this paper presents an optimization model in which the building energy system entirely consists of a pool of predefined types of devices, thus enabling a higher modeling accuracy of the individual types. The model considers the aforementioned heat generators as well as renewables like photovoltaics and solar thermal collectors. Batteries and thermal buffer tanks are included as storage technologies.

The model is applied to three residential buildings significantly differing in size and usage. The results indicate that gas boilers and combined heat and power units present the most economic options. The findings further suggest that photovoltaics are economically feasible whereas batteries are currently not profitable. The developed model offers a higher modeling accuracy than the simplified model at the costs of long computing times. Thus, the simplified model is further used to limit the search space of the developed model, reducing the deviation from the developed model in terms of accuracy while still maintaining a viable computation time.

Keywords – optimization; building energy system, mixed integer linear program

1 Introduction

The transition towards a more energy efficient and environmentally friendly economy is a recognized objective of the European Union [1]. In Germany, this concept is known as ‘Energiewende’ and aims at reducing greenhouse gas emissions and increasing electricity generation from renewable energy sources (RES) as well as achieving higher energy efficiency in general [2]. In the context of buildings, energy savings can for example be achieved by installing more efficient heating devices and by improving their control strategy.

Currently, most studies using exact optimization methods for determining the optimal design, size and operation of building energy systems (BES) rely on large simplifications. Often, the heating devices' nominal powers are chosen from a continuous range between a lower and an upper bound [3-8], leading to solutions that are not available in reality. This approach is hereafter referred to as Simplified Approach.

Thus, this paper extends previous works by presenting an optimization model that exclusively chooses heating devices from a previously defined pool of types that are available in reality and schedules their operation. In addition, modeling a pool of realistic device options rather than simply scaling the device dimensions allows for more information regarding each type to be included, such as specific efficiency values for each type, resulting in a higher modeling accuracy. Furthermore, this approach ensures that the computed, optimal configuration exists and can be purchased as well as installed. Additionally, this paper analyses if the aforementioned Simplified Approach can be used to reduce the pool of available device options of the more accurate model in order to reduce the computing times.

The following section describes the implemented optimization model. Section 3 presents the analyzed scenario and used boundary conditions. Afterwards, the results are explained in section 4. Finally, in section 5 conclusions are drawn.

2 Model

The optimization model is written as a mixed integer linear program (MILP) and is designed for computing the optimal BES for residential buildings, considering the demands for space heating, domestic hot water and electricity. The possible generation technologies comprise gas boilers, micro combined heat and power (CHP) units, air to water heat pump (HP) units, electrical heaters (EHs), photovoltaic (PV) modules as well as solar thermal collectors (STCs). Furthermore, storage devices such as thermal energy storage (TES) units and batteries (BAT) as well as peripheral devices like inverters (INV) are considered.

An hourly temporal resolution is chosen as a trade-off between accuracy and problem size. This resolution reasonably reflects seasonal influences as well as fluctuations within single days of the heating and electricity demands of buildings. As the computational effort of a full year calculation exceeds current resources, the optimization model is formulated according to [9] for D typical days with weighting factors w_d for each typical day d , representing the original, full year input data.

The following subsections describe the objective function and the economic and technical constraints of the optimization model. Furthermore, a brief comparison with the Simplified Approach is given. Due to the limited space of this publication, the description is shortened to the key equations.

2.1 Objective function

The optimal BES configuration minimizes the annualized costs that comprise investments (c_{inv}), costs for operation and maintenance ($c_{\text{o\&m}}$), demand related costs (c_{dem}) and metering costs (c_{met}). Additionally, revenues from electricity feed-in ($r_{\text{f-in}}$) and governmental subsidies (r_{sub}) are considered:

$$\min c_{\text{inv}} + c_{\text{o\&m}} + c_{\text{dem}} + c_{\text{met}} - r_{\text{f-in}} - r_{\text{sub}} \quad (1)$$

2.2 Economic constraints

The economic modeling is based on the German engineering guideline VDI 2067 [10]. A more detailed description including the implemented equations can be found in [6].

Initial investments for each device are reduced to annual payments. The operation and maintenance costs are device- and type-specific, fixed percentage rates of the investment costs, according to [10]. Demand related costs are split into the gas consumption of CHP units and boilers as well as electricity imports from the utility grid. Metering costs only occur if an additional gas metering device is installed, which is required if the optimal BES comprises either a CHP unit or a gas boiler. Revenue is generated by supplying electricity from PV and CHP to the utility grid at a constant feed-in remuneration. For the case of Germany, governmental subsidies are only considered for CHP units and are based on the electricity generated by the CHP unit.

2.3 Technical constraints

Technical constraints comprise the operation of the heat and electricity generation and storage devices, the building's energy balances and physical limitations such as the available area for PV and STC.

In general, at most one type of each device dev (e.g. HP, CHP, etc.) from the pool of available types I_{dev} (e.g. HP1, HP2, etc.) can be purchased:

$$\sum_{i=1}^{I_{dev}} x_{dev,i} \leq 1 \quad (2)$$

In this equation, $x_{dev,i}$ denotes a binary variable that is 1 if type i of device dev is purchased and 0 otherwise.

The cumulated area of all PV and STC modules ($z_{dev,i}$) has to be less than or equal to the maximum, available area (A_{max}):

$$\sum_{dev \in \{\text{PV}, \text{STC}\}} \sum_{i=1}^{I_{dev}} z_{dev,i} \cdot A_{dev,i} \leq A_{\text{max}} \quad (3)$$

The relationship between $z_{dev,i}$ and $x_{dev,i}$ for PV and STC modules is

$$z_{dev,i} \leq A_{\text{max}} / A_{dev,i} \cdot x_{dev,i} \quad (4)$$

Devices can only be switched on, if they have been purchased before:

$$y_{dev,i,d,t} \leq x_{dev,i} \quad (5)$$

In (5), $y_{dev,i,d,t}$ is a binary variable that is 1 if type i of device dev is activated at time t on day d and 0 otherwise.

Every device can operate flexibly between a lower modulation level ($ml_{dev,i} \cdot \dot{Q}_{dev,i}^{nom}$) and its nominal heat output ($\dot{Q}_{dev,i}^{nom}$):

$$y_{dev,i,d,t} \cdot ml_{dev,i} \cdot \dot{Q}_{dev,i}^{nom} \leq \dot{Q}_{dev,i,d,t} \leq y_{dev,i,d,t} \cdot \dot{Q}_{dev,i}^{nom} \quad (6)$$

For heat pumps, instead of the nominal heat output, the nominal electricity demand is used, because the electricity demands of HP units only marginally depend on outer influences such as the weather dependency of the coefficient of performance.

The coupling between heat generation and the electrical side of each type is illustrated in (7), where $\varphi_{dev,i,d,t}$ describes each type's heat to power ratio and $P_{dev,i,d,t}$ the electricity demand or generation. The heat to power ratio φ is rather used than the power to heat ratio σ , because φ is applicable and intuitive for HP and EH, whereas σ is only common for CHP. We consider time constant performance factors for each boiler, CHP unit and EH. For HP units, hourly performance factors are computed based on the outside temperature and flow temperature according to the building's heating curve.

$$\dot{Q}_{dev,i,d,t} / \varphi_{dev,i,d,t} = P_{dev,i,d,t} \quad (7)$$

For gas boilers and CHP units, the gas consumption ($E_{dev,i,d,t}$) is computed with:

$$(P_{dev,i,d,t} + \dot{Q}_{dev,i,d,t}) / \eta_{dev,i,d,t} = E_{dev,i,d,t} \quad (8)$$

In (8), $\eta_{dev,i,d,t}$ stands for the total efficiency. For boilers, $P_{dev,i,d,t}$ is 0.

Solar components are assumed to always harvest the maximum available electricity or heat, therefore for PV and STC (6-7) are replaced with

$$\dot{Q}_{dev,i,d,t} = \eta_{th,dev,i,d,t} \cdot z_{dev,i} \cdot A_{dev,i} \cdot G_{d,t} \quad (9)$$

$$P_{dev,i,d,t} = \eta_{el,dev,i,d,t} \cdot z_{dev,i} \cdot A_{dev,i} \cdot G_{d,t} \cdot \eta_{INV} \quad (10)$$

In this set of equations, $\eta_{th,dev,i,d,t}$ and $\eta_{el,dev,i,d,t}$ represent the thermal and electrical efficiency, η_{INV} the average efficiency of all considered inverters and $G_{d,t}$ the solar irradiation on each module. As will be described further in section 3, 46 inverters are considered in this paper. As their efficiency ranges from 96 to 98% and only insignificantly affects the investment costs, an average efficiency for all inverters is used.

The inverter is sized according to the maximum generated electricity

$$\sum_i^{I_{PV}} P_{PV,i,d,t} \leq \sum_i^{I_{INV}} x_{INV,i} \cdot P_{INV,i}^{nom} \cdot \eta_{INV} \quad (11)$$

The TES unit links the building's total heat demand ($\dot{Q}_{d,t}^{dem}$), which is the sum of space heating and domestic hot water demand, with the heat generation from the gas boiler, CHP unit, HP unit, EH and STC. The energy balance of each TES type results in:

$$soc_{TES,i,d,t} = (1 - k_{TES,i}) \cdot soc_{TES,i,d,t-1} + \Delta t \cdot \frac{\dot{Q}_{TES,i,d,t}^{ch} - \dot{Q}_{TES,i,d,t}^{dch}}{\rho_W \cdot \kappa_W \cdot V_{TES,i} \cdot \Delta T_{max}} \quad (12)$$

In this equation, $soc_{TES,i,d,t}$ describes the TES's state of charge, $k_{TES,i}$ the TES's relative losses to the environment, ρ_W and κ_W the density and specific heat capacity of water, $V_{TES,i}$ the TES unit's water volume, ΔT_{max} the maximum temperature spread inside the TES unit, $\dot{Q}_{TES,i,d,t}^{ch}$ and $\dot{Q}_{TES,i,d,t}^{dch}$ the charging and discharging heat.

The charging and discharging heat are additionally constrained with

$$\dot{Q}_{TES,i,d,t}^{ch}, \dot{Q}_{TES,i,d,t}^{dch} \leq x_{TES,i} \cdot M \quad (13)$$

$$\sum_i^{I_{TES}} \dot{Q}_{TES,i,d,t}^{ch} = \sum_{dev \in \{BOIL, CHP, HP, EH, STC\}} \sum_{i=1}^{I_{dev}} \dot{Q}_{dev,i,d,t} \quad (14)$$

$$\sum_i^{I_{TES}} \dot{Q}_{TES,i,d,t}^{dch} = \dot{Q}_{d,t}^{dem} \quad (15)$$

Equation (13) represents a so called big-M constraint which implies that $\dot{Q}_{TES,i,d,t}^{ch}$ and $\dot{Q}_{TES,i,d,t}^{dch}$ are 0 if $x_{TES,i}$ is 0. If $x_{TES,i}$ equals 1, the entire heat generation (14) and the entire heat demand (15) are taken into account for this specific TES unit. The value of M has to be an upper bound for the left hand side. In this paper, the design heat load (\dot{Q}_{DHL}) has been used.

The storage balances of the battery units are formulated similarly, further considering the battery's efficiency $\eta_{BAT,i}$ for charging and discharging.

$$soc_{BAT,i,d,t} = (1 - k_{BAT,i}) \cdot soc_{BAT,i,d,t-1} + \Delta t \cdot \frac{\eta_{BAT,i} \cdot P_{BAT,i,d,t}^{ch} - \frac{P_{BAT,i,d,t}^{dch}}{\eta_{BAT,i}}}{C_{BAT,i}} \quad (16)$$

Compared with the TES unit, the values of M can be set to the battery's maximum charging and discharging power. Furthermore, the battery's charging and discharging powers can be computed through an electricity balance of the building:

$$P_{d,t}^{dem} + \sum_i^{I_{BAT}} (P_{BAT,i,d,t}^{ch} - P_{BAT,i,d,t}^{dch}) + \sum_i^{I_{HP}} P_{HP,i,d,t} + \sum_i^{I_{EH}} P_{EH,i,d,t} \quad (17)$$

$$= P_{CHP,d,t}^{use} + P_{PV,d,t}^{use} + P_{imp,d,t}$$

In (17), $P_{imp,d,t}$ stands for the electricity imported from the grid.

The sum of the amounts of fed-in and self-consumed electricity has to be equal to the generated power of CHP and PV:

$$\sum_i^{I_{dev}} P_{dev,i,d,t} = P_{dev,d,t}^{use} + P_{dev,d,t}^{sell} \quad (18)$$

This model is written considering a set of typical demand days instead of a full year with 365 consecutive days. As a result, the storage's final state of charge has to be equal to its initial state of charge for each day:

$$soc_{dev,i,d,0} = soc_{dev,i,d,T} \quad (19)$$

Furthermore, the state of charge has to be less than or equal to one and can only be positive, if the storage type has been purchased. This is ensured with

$$soc_{dev,i,d,t} \leq x_{dev,i} \quad (20)$$

The TES is designed for a maximum temperature spread of ΔT_{\max} which can be provided by all heating devices except the heat pumps, as they are typically only able to provide a small temperature rise of $\Delta T_{\max}^{\text{HP}}$. As a result, the heat pumps' operation is further constrained by their maximum, feasible temperature spread:

$$\sum_i^{I_{\text{TES}}} \text{SOC}_{\text{TES},i,d,t} \leq 1 - y_{\text{HP},i,d,t} \cdot (1 - \Delta T_{\max}^{\text{HP}} / \Delta T_{\max}) \quad (21)$$

2.4 Simplified Approach

This paper focuses on the optimal selection of heating devices. In (2), the selection is described with binary variables with which a previously defined heating device can be integrated into the BES. In many other studies using MILP, such as [3-8] heating devices are assumed to be available in a continuous range of nominal powers between a lower ($\dot{Q}_{dev}^{\text{nom},\min}$) and an upper bound ($\dot{Q}_{dev}^{\text{nom},\max}$):

$$x_{dev} \cdot \dot{Q}_{dev}^{\text{nom},\min} \leq \dot{Q}_{dev}^{\text{nom}} \leq x_{dev} \cdot \dot{Q}_{dev}^{\text{nom},\max} \quad (22)$$

This approach suffers from a series of potential inaccuracies, such as the computation of investment costs, the devices' modulation capabilities and efficiencies. The investment costs are commonly approximated with a fixed initial cost for each device that can be taken into account through the binary variable x_{dev} and a variable cost fraction that can be priced with the chosen nominal heat output $\dot{Q}_{dev}^{\text{nom}}$. This approximation of the investments through a linear regression introduces an inaccuracy in the economic evaluation.

Regarding the technical side of the optimization problem, a model has to be found that fits all types of each device. For instance, the minimum modulation levels of all CHP units analyzed in this paper range from 32% to 100%, with an average value of 79% and a median of 100%. The power to heat ratios also vary widely from 0.33 to 0.56 with average and median values of 0.42. Thus, this example illustrates that introducing a model that represents all types of one device can also introduce significant inaccuracies.

3 Scenario

The described mathematical model is applied to the design of the BES of three different buildings significantly varying in size as well as thermal and electrical demands. The buildings comprise a single-family house (SFH), a multi-family house (MFH) and an apartment building (AB). The main specifications of each building are summarized in Table 1.

Table 1. Investigated buildings

Building	Residents per apartment	Design heat load in W
SFH	2	6500
MFH	2, 3, 3	25700
AB	2, 2, 2, 2, 3, 3, 4, 5	33500

The electricity demand of each apartment is computed based on [11]. The design heat load is determined according to DIN EN 12831 and the hourly heat demand profiles are computed with a simplified building model [12]. The domestic hot water demand profiles are computed with a combination of the user's occupancy based on [11] and the daily tap water usage of residential buildings provided by [13].

The pool of considered conventional heating devices is summarized in Table 2. The table describes the number of considered types per device, their minimum and maximum as well as average (in parentheses) nominal heat output and investment costs. The heat pumps' nominals are given at 2 °C outside temperature and 35 °C flow temperature. Heat pumps are controlled only with an on-off signal, while the other devices can operate in part load.

Table 2. Pool of conventional heating devices

Device	No. types	Nominal in kW	Investments in €
Boiler	15	11.0 – 66.3 (29.5)	1325 – 4255 (2385)
CHP	17	2.5 – 36.1 (12.5)	8927 – 35000 (20000)
El. heater	16	2.0 – 12.0 (5.8)	154 – 225 (188)
Heat pump	20	3.1 – 17.4 (8.6)	3792 – 16980 (8090)

Renewable and peripheral devices include PV, STC and INVs. The pool of included types of each device is described in Table 3. The PV's nominal values refer to the electricity generation at 800 W/m² solar irradiation and 20 °C ambient temperature. The STC's nominals stand for the heat production at the same outdoor conditions and the inverter's nominals for the DC input power.

Table 3. Pool of renewable and peripheral devices

Device	No. types	Nominal in kW	Investments in €
PV	17	0.15 – 0.23 (0.20)	164 – 352 (251)
STC	13	0.42 – 1.32 (1.11)	190 – 817 (466)
Inverter	46	1.6 – 28.6 (9.6)	585 – 4171 (1699)

Storage devices, namely TES and BAT are available for each BES. The investment costs, capacities and number of considered types are summarized in Table 4. The capacity of TES units is measured in m³ water volume while the batteries' capacity is measured in kWh electricity.

Furthermore, typical weather data for the German state North Rhine-Westphalia is used [14]. The inputs consist of the ambient temperature as well as solar irradiation on a 35° tilted surface with southern orientation,

Table 4. Pool of storage devices

Device	No. types	Capacity in m ³ (TES) or kWh (BAT)	Investments in €
TES	28	0.1 – 2.0 (0.6)	419 – 2055 (990)
Battery	24	2.3 – 11.6 (6.4)	4795 – 14538 (10527)

which is required for the PV and STC modules.

The observation period for all computations is 10 a, the assumed interest rate is 5%, and the electricity and gas prices are 0.266 €/kWh and 0.065 €/kWh respectively. Electricity feed-in remuneration for CHP units is 0.054 €/kWh and for PV units 0.1231 €/kWh.

In order to limit the computational effort for the optimization, the input data is clustered into twelve representative days, according to [9].

All optimization problems are formulated with Python and solved with Gurobi 6.0.0 on a Windows computer with 6 cores and 32 GB of RAM. The tolerated optimality gap is set to 1%.

4 Results

The results of the developed and simplified models are shown in Table 5. Heat pumps have never been chosen in any of the optimization runs. Instead, CHP units or boilers are chosen as primary heating devices, while EH and STC are installed as additional devices. All models favor PV modules, whereas STC are only installed to cover minor heat demands.

The results of the SFH illustrate that the technical models of boiler equipped buildings are similar in the developed and simplified model, while the economic models introduce significant deviations. The objective values of both models differ by approximately the amount that the investment costs differ. The relative deviation between both models is approximately 7.1%.

The AB on the other hand shows that the CHP unit's operation is very inaccurate in the Simplified Approach. The investment costs are almost the same, while the objective values which combine the investments and operating costs, differ by 11.4%. This effect is mainly due to the representation of CHP units in the Simplified Approach. In this model, the pool of considered CHP units is averaged to one representative CHP unit. The power to heat ratio of this representative CHP unit is 0.1 less than in the more accurate, developed model, leading to deviations of approximately 7200 kWh of gen-

Table 5. Results of the developed (dev.) and simplified (simp.) models

	SFH		MFH		AB	
	Dev.	Simp.	Dev.	Simp.	Dev.	Simp.
Cap. boiler [kW]	14.20	11.00	14.20	23.49	14.20	12.85
Cap. CHP [kW]	-	-	12.00	-	20.00	15.79
Cap. EH [kW]	4.50	-	-	3.79	-	4.86
Area PV [m ²]	37.34	40.00	38.97	38.22	38.97	40.00
Area STC [m ²]	0.90	-	-	1.78	-	-
Volume TES [m ³]	0.12	0.26	0.98	0.13	1.50	2.00
Investments [€/year]	1010	1246	3007	1324	3870	4016
Obj. value [€/year]	3212	3440	10505	11316	20772	23148
Runtime [s]	29731	16	33768	23	6913	18

erated electricity per year. This amount roughly equals the monetary difference between both models.

The main drawback of the developed model is the long computing time, which is more than 300 times higher than in the Simplified Approach. The results of the Simplified Approach are therefore used to decrease the solution space of the developed model – this methodology is therefore hereafter referred to as the Combined Approach. If the Simplified Approach chooses a certain device for the optimal BES, the solution space in the combined approach is limited to the next bigger and next smaller, existing type. If the Simplified Approach does not choose a certain device, e.g. a heat pump, only the smallest available type of this device is considered in the solution space. In this manner, the inaccuracies regarding technical and economical modelling of the Simplified Approach are avoided for the price of a potentially excluded optimal solution.

The results of the Combined Approach and the relative, monetary differences from the results of the developed model are presented in Table 6. The combination of both approaches reduces the overall errors in the objective values from between 7.1% and 11.4% to values between 1.0% and 5.8%. The runtime (including the runtime of the Simplified Approach) increases moderately, so that the Combined Approach provides a good trade-off between accuracy and computing times.

Table 6. Results of the combined approach (comb.) and relative monetary differences (diff.)

	SFH		MFH		AB	
	Comb.	Diff.	Comb.	Diff.	Comb.	Diff.
Cap. boiler [kW]	14.20		26.00		14.20	
Cap. CHP [kW]	-		-		13.50	
Cap. EH [kW]	2.00		4.50		6.00	
Area PV [m ²]	38.97		37.34		39.36	
Area STC [m ²]	0.90		1.84		-	
Volume TES [m ³]	0.20		0.12		2.00	
Investments [€/year]	1075	6.5%	1061	-64.7%	3628	-6.2%
Obj. value [€/year]	3245	1.0%	11117	5.8%	21414	3.1%
Runtime [s]	26		30		32	

5 Conclusions

This study presents a mixed integer linear program for the optimal design and operation of residential building energy systems. In comparison with related studies, the modeling accuracy is largely improved by considering real devices and their specific characteristics (developed model) instead of scaling one representative type of device (Simplified Approach).

Both models are applied to three residential buildings. The results reveal that the Simplified Approach leads to large deviations from the developed

model regarding investments as well as operational costs. On the other hand, the developed model requires long computing times. Until computers or optimization solvers improve, these computing times as well as the gap between both models can significantly be reduced, by using the results of the Simplified Approach to limit the solution space of the developed model.

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