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Quantifying the operational flexibility of building energy systems with thermal energy storages

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HIGHLIGHTS

- Quantification method for flexibility of building energy systems developed.
- Heat pumps and combined heat and power plants analyzed.
- Thermal storage as central element of the analysis.
- Possibility of the aggregation on a city district level.
- Technical comparison to battery storages.

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ABSTRACT

The increasing share of fluctuating renewable energy generation in the energy system increases the need for flexibility options. Building energy systems (BES) with their corresponding thermal energy storages (TES) can be one option for supplying flexibility. To use this option efficiently, a framework to quantify the flexibility of the BES is necessary. It is found that the flexibility of a BES can hardly be described with one single flexibility indicator. Therefore, this paper develops a method to analyze the flexibility of BES in terms of time, power and energy. Different influencing factors are considered, like the heat generator and the thermal storage size. Additionally, the option to aggregate the different flexibility measures on a city district level is addressed. This is necessary as single buildings have a minor impact on higher level energy systems. Finally, a comparison to other flexibility options like battery storage is discussed.

1. Introduction

In the following years, the energy system will face major challenges due to the introduction of renewable energy sources (RES) to the electrical grid. As the demand and supply side in the electrical energy system have to be balanced at each time step, flexibility options are needed to cover times with surplus or shortfalls of electricity. Different alternatives can be used to offer flexibility to the grid (e.g. energy storages, Demand Side Management (DSM), flexible conventional power plants or the electricity grid infrastructure) [1]. Flexibility measures are needed in different time scales as it is shown exemplarily with the analysis of energy storage capacities by Makarov et al. [2].

Additionally to the requirements that are posed by the integration of RES, the building sector is facing a trend towards decentralized, more efficient technologies to cover the heat demand. These technologies incorporate heat pumps (HP) and combined heat and power (CHP) plants. With an increasing share of these technologies installed in the electrical distribution grid, their integration to the electrical grid needs to be planned similar to the integration of RES. This is exemplarily shown in [3] where the problems of heat-driven HP and CHP plants are emphasized.

As shown by Arteconi et al. [4] and Müller et al. [5], the coordinated operation of decentralized building energy systems (BES) in the context of a DSM could be an option for the integration of both RES and energy-efficient BES to the energy system. Brouwer et al. [6] have also demonstrated the economical potential of demand response measures. Teng et al. [7] state that the usage of HP in DSM measures can reduce "balancing cost, required back-up generation capacity and cost of replacing curtailed RES output with alternative low-carbon technology to achieve the same emission target". The potential compared to conventional electrical storage options is mainly driven by the lower cost of TES that is discussed by Østergaard [8]. The flexibility options in the building sector are introduced in the combination of different heat generators with

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Nomenclature

C	capacity of battery
c	heat capacity of water
i	index for sum
N	number of cycles
n	number of layers
Q	thermal energy
T	temperature
t	time
V	volume
Greek letters	
α	dimensionless power
β	dimensionless energy
ϵ	energy
η	efficiency
π	power
ρ	ramp-up capability
ρ_W	density of water
σ	power-to-heat ratio
τ	temporal flexibility
ξ	integration variable
Abbreviations	
BES	building energy systems
BPS	building performance simulation
CHP	combined heat and power
DHW	domestic hot water
DOD	depth-of-discharge
DSM	demand side management
EHG	electrical grid coupled heat generator(s)
HP	heat pump(s)
HR	heating rod(s)
RES	renewable energy sources
SH	space heating
TES	thermal energy storage
TRY	test reference year
Subscripts	
avg	average
bat	battery
build	belonging to the building
cycle	per storage cycle
delayed	delayed flexibility
el	electrical
flex	flexibility
forced	forced flexibility
life	life of the battery
max	maximum
min	minimum
neg	negative
nom	nominal
pos	positive
ref	reference case
stor	belonging to the storage
th	thermal
year	whole year

corresponding thermal energy storages (TES) [5]. As TES, the thermal mass of the building structure itself and technical TES with phase change materials or sensible materials (e.g. water) as medium can be used [9]. The considered heat generators in the present work are HP and CHP plants, as their operation can directly influence the electrical grid. These two types of heat generators are called electrical-grid coupled heat generators (EHG) in the following.

As the operational flexibility of EHG competes against other flexibility options (e.g. energy storage technologies like batteries, pumped hydro storages or compressed air energy storages among other options mentioned in [10]), a general quantification method for the term flexibility is needed. If this method exists, different options for flexibility can be compared to each other in different key performance indicators. From the electrical grid side, the work on flexibility requirements shows some connecting elements. First of all, Kondziella and Bruckner [10] define two general types of flexibility that are needed. Positive flexibility is needed if the load is higher than the generation from renewable sources and negative flexibility is needed if the renewable generation exceeds the load. In this definition, a provision of positive flexibility means to either increase generation or decrease loads while negative flexibility requires to decrease generation or increase loads. This is also consistent to the definition of Ulbig and Andersson [11].

After this general description of flexibility, it is necessary to develop a framework in which the flexibility can be quantified. Lund et al. [1] mentioned that different approaches for energy flexibility measures are present and therefore a single number cannot describe flexibility properly. Several studies analyzed different aspects of flexibility quantification. Denholm and Hand [12] analyzed the influence of RES integration on the curtailment of electricity where the flexibility is characterized with the ability to modulate conventional power plants. A similar analysis is conducted by Kubik et al. [13] where the authors analyze the flexibility of conventional power plants with different fuels. Brouwer et al. [14] investigate the available reserve of conventional power plants and the properties of different power plant types that define the ability to deal with ramps. Huber et al. [15] studied the influence of increasing RES penetration on the ramps (change of power e.g. in one hour) in the electrical grid for different countries. Compared to this, Saarinen et al. [16] studied the power of the residual load (load minus RES generation) and the needed storage capacities to cover different time frames. Ulbig and Andersson [11] developed a framework based on the work of Makarov et al. [17] that allows to quantify the operational flexibility of different energy flexibility options in a generalized way. These authors focus the ramping capability, the power and the energy in their work. All these figures can be calculated in both directions (positive/negative) and a methodology is given to combine/aggregate different flexibility options.

For the building side, often case studies in which the flexibility of the EHG is already utilized are using the term "flexibility". For example, this can be the case of a CHP plant in a district heating grid [18] or the operation of heat pumps with different TES [19]. Additionally, the operation of electric water heaters, air conditioners or refrigerators is described [20]. In another work, the interaction of HP, storages (thermal and electrical) and photovoltaics is analyzed [21]. Optimization methods are used to operate buildings according to electrical grid constraints [22] or to minimize the cost in a virtual power plant consisting of CHP plants, thermal and electrical energy storages and renewable energy sources [23]. Pedersen et al. [24] consider a portfolio of HP systems that are operated in