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Quantifying demand flexibility of power-to-heat and thermal energy storage in the control of building heating systems

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HIGHLIGHTS

- Water, phase change material, and thermochemical material tanks are integrated for optimal control.
- Demand flexibility of thermal energy storage tanks integrated with a building heating system is quantified.
- Flexibility indicators representing demand flexibility are calculated for reference and optimal control.
- A power flexibility indicator is introduced, the instantaneous power flexibility.

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ABSTRACT

In the future due to continued integration of renewable energy sources, demand-side flexibility would be required for managing power grids. Building energy systems will serve as one possible source of energy flexibility. The degree of flexibility provided by building energy systems is highly restricted by power-to-heat conversion such as heat pumps and thermal energy storage possibilities of a building. To quantify building demand flexibility, it is essential to capture the dynamic response of the building energy system with thermal energy storage. To identify the maximum flexibility a building's energy system can provide, optimal control is required. In this paper, optimal control serves to determine in detail demand flexibility of an office building equipped with heat pump, electric heater, and thermal energy storage tanks. The demand flexibility is quantified using different performance indicators that sufficiently characterize flexibility in terms of size (energy), time (power) and costs. To fully describe power flexibility, the paper introduces the instantaneous power flexibility as power flexibility indicator. The instantaneous power flexibility shows the potential power flexibility of TES and power-to-heat in any case of charging, discharging or idle mode. A simulation case study is performed showing that a water tank, a phase change material tank, and a thermochemical material tank integrated with building heating system can be designed to provide flexibility with optimal control.

1. Introduction

With the increasing application of distributed energy generation, attuning energy consumption to energy generation has become an attractive mitigation strategy for intermittency issues [1]. The ability to control electrical energy consumption based on power grid incentives is called demand response (DR) [2]. Special attention has been given to the energy consumption of buildings which plays a major role in global energy demand [3]. The DR of buildings is comprised of the ability to control the electricity demand profile [3]. The deviation from the reference demand profile is the demand flexibility of buildings [3,4].

A summary of quantification methods for the energy flexibility of buildings is provided by Lopes et al. [3], in which characterization of energy flexibility refers to a demand increase as negative flexibility and a demand decrease as positive flexibility [5,6]. Nuytten et al. [7] calculated the energy flexibility of a combined heat and power (CHP) system with thermal energy storage (TES) wherein flexibility was related to shifting of the electrical consumption in time, expressed as the number of hours of delayed operation. The authors in [7] introduced the concept of forced and delayed flexibility. With forced flexibility, a period is determined in which a system is forced to store excess energy. Delayed flexibility describes a period in which a system is requested to postpone and reduce energy consumption, for instance, by discharging storage. The method of forced and delayed flexibility provides

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Nomenclature

C	available storage capacity
D	effective diffusion
h	specific enthalpy
J	optimal cost function
J_π	expected costs referring to policy π
k_m	mass transfer coefficient between evaporator/condenser and adsorber
l	duration
m	number of OC events
m_{ads}	mass adsorbate
n	number
N	planning horizon
p	pressure
q	adsorbate – amount of refrigerant (water) in the solid phase of dry material (zeolite13X)
Q_s	adsorption enthalpy
t	time
u	positive constant velocity
u_t	control variables referring to optimal control
U_t	control constraints
V_{dot}	volume flow
x	spatial coordinate referring to the one-dimensional convection-diffusion equation
x_t	state variables referring to optimal control
T	temperature

Greek symbols

α	positive constant coefficient
Δ,δ	difference
ε	random parameter referring to the occupancy rate in optimal control
η	efficiency
θ	dependent variable
λ	thermal conductivity [W/m K]
π	policy
ρ	density [kg/m^3]

Subscripts

ch	charging
comp.	compartments
down	downwards
eq	referred to p as equilibrium
i	referred to x as i-th segment of x
inst	instantaneous
liq	referred to T as liquid
max	maximum
min	minimum
n	referred to t as time step of t
ref	reference
sol	referred to T as solid
up	upwards

Abbreviations

APX	Amsterdam power exchange
BRCM	building resistance-capacitance modeling
BTM	building thermal mass
CHP	combined heat and power
COP	coefficient of performance
DP	dynamic programming
DR	demand response
FD	finite difference
FF	flexibility factor
HP	heat pump
HT	heat transfer
HVAC	heating, ventilation, and air conditioning system
HX	heat exchanger
LDF	linear driving force
OC	optimal control
PCM	phase change material
RC	resistance-capacitance
TCM	thermochemical material
TES	thermal energy storage
TMY	typical meteorological year

information about time periods with constant power but does not consider power variations over time. Based on the work of D'hulst et al. [8] and Reynders et al. [9], Stinner et al. [6] introduce power flexibility using power curves, defined as a time-dependent difference between maximum and reference power. Power flexibility is required to determine flexibility towards power grid stabilization. Recent studies about demand flexibility of buildings suggest costs as an additional dimension of flexibility [4,10]. De Coninck et al. [4] use conventional utility rates, including cost curves, associated with costs of flexibility. In the study of [4], flexibility refers to shifts in the power demand of the heating, ventilation, and air conditioning system (HVAC). Le Dreau et al. [10] suggest the flexibility factor as performance indicator measuring the potential flexibility during operation. The flexibility factor considers variable electricity price periods and indicates whether the controlled system is flexible enough to shift the heating demand from high to low-price periods. An overview of flexibility indicators is given by Clauβ et al. [11]. The review describes performance indicators that relate to all dimensions of demand flexibility. The review also presents an overview of flexibility indicators that are assumed in conventional and modern, optimal control strategies. Clauβ et al. [11] concluded that multiple indicators such as self-consumption, self-generation, flexibility factor, storage capacity, storage efficiency are not yet considered in optimal and model-predictive control.

Potential demand-side flexibility sources have been determined by relevant studies [4–10,12–20]. Electrical power-to-heat and thermal energy storage are identified as effective measures to provide flexibility [12–14,21]. Building-integrated TES technologies are classified into sensible (e.g. building thermal mass (BTM) and water), latent (e.g. phase change materials (PCM) and ice), and thermochemical materials (TCM) [22]. They can also be categorized as active TES (water, ice, PCM, and TCM tanks) and passive TES (BTM and PCM panels) [23,24]. Thermal energy storage can be an effective solution to attune energy supply and demand, combined with electrical appliances. To activate TES tanks with power-to-heat conversion, the working temperature range of the heat storage medium determines the minimum and maximum flexibility. For water tanks, charging and discharging temperatures in space heating (SH) and domestic hot water (DHW) supply is typically between 21 °C and 95 °C [25]. In the case with charging temperatures higher than 95 °C, it is required that the tank equipment can manage high pressures. The use of thermal oil instead of water as storage medium can compensate for higher temperatures but has a comparably lower heat conductivity and specific heat capacity [25]. Adequate materials used as PCM in SH and DHW are presented by Cabeza [26]. The review describes inorganic and organic PCM with melting points up to 120 °C. TCM systems typically hydrate (discharging) above 40 °C and dehydrate (charging) between 80 and 120 °C [27–30]. Latest advances in TCM development include salt hydrates, such as $CaCl_2{\cdot}6H_20$ or $SrBr_2{\cdot}6H_2O$ with dehydration temperatures down