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Grid support coefficients for electricity-based heating and cooling and field data analysis of present-day installations in Germany

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HIGHLIGHTS

- Two new metrics, the Grid Support Coefficients GSC_{abs} and GSC_{rel}, are proposed.
- They quantify the coincidence of a load profile and relative availability of electricity in the energy system.
- The method is applied to monitoring data of heat pumps, chillers and CHP units.
- The analysis reveals that today, most HVAC systems operate "grid-neutrally".
- A transition to "grid-optimal" operation requires large thermal storage capacities.

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ABSTRACT

A new method for assessing the grid interaction of a building's electricity consumption and generation is presented. It consists of the Grid Support Coefficients GSC_{abs} and GSC_{rel}. GSC_{abs} "weights" the electricity consumption profile with a time-resolved reference quantity which expresses the availability of electricity in the public grid (here: stock electricity price, residual load, cumulative energy consumption or fraction of wind and PV in the electricity mix). GSC_{rel} relates GSC_{abs} to the worst and best achievable values on a scale of -100 to 100 in order to increase the comparability of the results.

The new evaluation method is applied to analyze the electricity consumption and/or production of 52 different energy supply systems in buildings, where detailed monitoring data are available. These examples include twelve heat pumps or chillers in office buildings, 38 heat pumps in residential buildings and two combined heat and power units (CHP) in multi-family buildings, all located in Germany. The in-depth analysis shows that the analyzed present-day buildings predominantly consume electricity at times with a low or average electricity availability. Optimal scheduling of all heat pumps could flatten the residual load significantly. In order to achieve this, thermal storages several times larger than the ones currently installed would be required.

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1. Introduction

1.1. Increasing fluctuations in the availability of electricity due to renewable energy

According to the Federal government's *Energy Concept*, Germany aims to reduce its greenhouse gas emissions, as compared to 1990, by 80% by the year 2050 and to phase out its last nuclear power plants by 2022, substituting them mostly with renewable energies [1,2]. As of November 2014, wind and photovoltaic (PV) plants represent 20% and 22% of the total installed generation capacity, respectively. Wind and PV plants accounted for 9.5% and 5.8%, respectively of Germany's 2013 net electricity production of 537 TW h [3]. On the sunniest days, renewable energy production has already exceeded demand [3], but the fraction of renewables will rise further: the Grid Development Plan 2013 published by the German transmission system operators assumes that wind and PV plants will account for 41% of the net electricity production in 2023 and 57% in 2033 (acc. to scenarios 2023b and 2033b) [4].

The increasing share of fluctuating renewable energy carriers in the energy system leads to an increasing volatility in the electric energy system. Since supply and demand need to match at each time point, a reliable electricity supply based on renewable energies therefore requires flexibility measures. These measures, which are

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Nomenclature

air	ventilation heating	inst	installed
CCC	Concrete Core Conditioning	n	total number of time steps
CCH	compression chiller	NPS	near-surface perimeter strip elements
CEC	(non-renewable) cumulative energy consumption ($kW\,h_{prim}/kW\,h_{el}$)	noHP	without heat pumps
CHP	combined heat and power	op	operation
CSP	ceiling suspended radiant panels	P	power
d	day	PLR	part load ratio
ecdf	empirical cumulative probability density function	Rad	radiators
EEX	EEX day-ahead price (EUR/MW h)	RES	residual load (GW)
fl	full load	RFC	radiant floor conditioning
G	grid-based reference quantity	SOC	state of charge
GSC_{abs}	absolute Grid Support Coefficient	supp	grid-supportive
GSC_{rel}	relative Grid Support Coefficient	t, T	time
h	hour	TABS	thermally activated building systems
HP	heat pump	WPV	fraction of wind and PV in the electricity mix (%)
HVAC	heating, ventilation and air conditioning		

comprehensively summarized by Lund et al. [5], include grid ancillary services (at time ranges from milliseconds to days or even months), energy storage, supply-side flexibility, advanced energy conversion processes (e.g., hydrogen, power-to-liquid), strengthening of the grid infrastructure and demand side management.

Behrangrad defines demand side management (DSM) as modifications in the demand side energy consumption pattern to foster better efficiency and operations in the electrical energy system. It is further categorized into energy efficiency (EE), which comprises measures to reduce the required energy, and demand response (DR), which describes changes in electrical usage by end-use customers from their normal consumption patterns in response to variable prices or other incentive payments. [6]

In this paper, the possible use of the electricity consumption of heat pumps and chillers as flexible loads, as well as the electricity production of CHP units as flexible producers (i.e. demand response participants) is evaluated. The operation profiles of heat and cold generators can be altered either by using technical thermal storages, or by changing the delivery trajectory of thermal energy to the conditioned zones, thus using the building itself as a heat storage, or by dynamic "fuel-switching" between different heat and cold generators (e.g. a heat pump and a gas boiler). In this study, the use of technical thermal storages is analyzed.

The electricity consumption and production associated with heating and cooling is viewed as significant for demand response for the following reasons: First, the building sector has a sizeable energy demand, accounting for nearly 40% of Germany's final energy consumption [7]. Second, the simulation and analysis of future German energy systems with a high fraction of renewables shows that the heating sector, which is currently still dominated by fossil fuels (90% of all residential buildings built between 1993 and 2010 in Germany are heated using oil or gas [8]), will likely transform to a higher fraction of heat pumps, which consume electricity and can hence contribute to electric load shifting [9]. Third, the collectivity of buildings has a very high thermal inertia and is thus able to store large quantities of thermal energy on a time scale of hours with small temperature differences, provided that the building mass can be thermally activated [10].

This study focuses on demand-response in terms of energy with a time scale of hours because the power and dynamic response capabilities of typical heat and cold generators are insufficient for shorter time scales and tasks like frequency control, whereas the thermal storage potential of buildings is usually too small for longer time scales. The electricity consumption structure is shifted according to the availability of electricity in the electric energy system, thus providing additional demand flexibility in the electricity market. As has been found in previous studies, increased demand side flexibility is required to balance fluctuating generation, leads to lower spot and peak electricity prices for the consumers and reduces the ability of generating companies to exert market power [5,11]. In conclusion, it has an overall beneficial effect on the market.

One prerequisite for load shifting is sufficient transmission capacity in the electric grid. For a limited number of demand response participants located mainly in urban areas with a strong electric grid infrastructure, it appears feasible that this condition is currently met. Therefore, limitations stemming from limited transmission capacity are not considered in this study. In future scenarios with a significantly higher number of demand response participants, additional investment into the electric transmission and distribution grids is likely to become necessary. Furthermore, any heating and cooling strategies must comply with various other requirements to the operation of HVAC systems such as indoor thermal comfort and energy cost, since a high user acceptance is prerequisite for large-scale application of demand response. User acceptance can be increased by certain economic incentive systems such as the ones presented in [6], which are not discussed in this paper as it focuses on the technical potential only.

1.2. Review of load matching and grid interaction indicators and field data evaluations

A major part of ongoing research on the grid interaction of buildings is associated with net-zero energy buildings with local electricity production. The focus of this research has been on the mismatch problem, i.e. the difference between local energy generation and demand, and ways to reduce the mismatch, e.g. by means of thermal and electrical storages and adapted control strategies. Notable indicators include the *Load cover factor* [12], which represents the fraction of the load covered by local production; the *supply cover factor* [12], which represents the fraction of the locally produced electricity consumed on-site, as well as derivatives of these metrics (self-consumption factor [13], shared area percentage index, excess supply percentage index [14]). The methodology of the *extended on-site energy fraction/on-site energy matching indices* for electricity, heating and cooling developed by

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