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Development of a data driven approach to explore the energy flexibility potential of building clusters

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HIGHLIGHTS

- A data driven model was developed to simulate a generic building cluster.
- Statistical occupancy models were developed and applied to buildings.
- A building portfolio was set up with regard to archetypes and number of households.
- The uncertainty of the energy flexibility caused by uncertain occupancy was quantified.

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ABSTRACT

With the growing use of renewable energy sources, the stability of electrical power systems can be seriously affected by fluctuations in the available power. As one of the potential solutions for this new challenge, the energy flexibility of buildings has become a focus for research and technological development. Most studies have focused on single buildings, with only a few studies on building clusters in which the building models were usually oversimplified in that they did not consider different building types or their thermal characteristics, their occupancy or their occupants' behaviour. In this paper, we describe a data driven approach to simulating a generic building cluster that could resemble any mix of building archetypes and occupancy. The energy flexibility potential of apartment building clusters was estimated by using data from surveys and available statistics in Denmark for the worst case scenario, i.e. when the end users do not allow any disturbance when they are at home, so that energy flexibility is only available when residents are not at home. In this scenario, no energy flexibility is assumed when buildings are occupied, which yields a conservative estimation. The uncertainty of the energy flexibility potential due to uncertain occupancy and various archetypes was quantified for different scales of building cluster. The resulting hybrid-model is a combination of a building model and an occupancy model and includes the different factors that influence the potential energy flexibility of buildings. The results show that the uncertainty of the energy flexibility decreases when the aggregated number of buildings increases. The uncertainty of energy flexibility was less than 10%, when about 700 households were aggregated. This approach can be used to simulate building energy flexibility for district or even regional level energy planning when the intention is to use the available flexibility to address the challenges caused by fluctuation in the power available from renewable energy sources.

1. Introduction

The use of renewable energy resources is increasing rapidly. In EU countries, at least 20% of total energy demand must come from renewables by 2020 [1]. Denmark plans to be fossil-fuel free by 2050 [2]. The high penetration of intermittently available renewable energy sources has already created a desperate need for increased flexibility that would allow a power system to adapt to dynamic and changing conditions, such as balancing supply and demand on different time scales or supporting congestion management at various locations [3]. Buildings account for one third of total energy consumption in Denmark and most other developed countries, so creating flexible energy demand in buildings has considerable potential. In future smart cities demand response and the energy (demand) flexibility of buildings are likely to

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play a significant role.

The energy flexibility in buildings is often quantified as the deviation of electricity consumption under different scenarios of electricity costs and thermal comfort provision [4]. Flexibility characteristics were described in detail in a recent publication [5]. The study was based on the assumption that the system providing flexibility is able to respond to an external penalty signal such as dynamic energy pricing. Six characteristics are then identified as (1) the delay time from energy price changes to the effect appears in energy demand, (2) the maximum power change in demand, (3) the time it takes to reach the maximum power change, (4) the total time of energy demand change, (5) the total decreased demand and (6) the total increased demand. The thermal comfort of building occupants is a constraint on flexible operation, so it has become a common approach to calculate the energy flexibility of buildings, especially regarding heating, ventilation and air-conditioning (HVAC) systems and thermal mass, by using pre-defined upper and lower temperature bounds, such as in [6] and [7]. In [8] the comfort range was more dynamic with comfort temperature determined using occupancy rate which refers to the ratio of occupants to the maximum amount of occupants.

Demand response and energy flexibility must be implemented at a large scale if the accumulated energy flexibility is to reach a magnitude that can be meaningful for energy providers. To the best knowledge of the authors, there are only a few publications on demand response and energy flexibility at the building cluster level. Vigna et al. [9] presented an overview of the concept of building clusters and its relevant concepts. A building cluster was defined from the perspective of building and energy grid interaction. In this definition, a building cluster is an aggregation of buildings which can be managed by a common agent such as a utility company, to exploit the energy flexibility of the building cluster. Studies have shown that the energy flexibility of a building is greatly influenced by both building physical characteristics and occupancy pattern of the residents [10–12]. A review of large scale demand response estimation studies [13] conducted in 2015 concluded that they used oversimplified building models that did not consider different building types or their thermal characteristics and occupants' behavior. Very few studies have appeared since 2015.

Li et al. [14] developed a forecasting model to investigate resource allocation within a building cluster while maintaining indoor thermal comfort. Three small and medium-sized DOE reference office buildings were included. A smart building cluster was studied for demand response [15]. In this study, building loads were modelled but not buildings. Georges et al. [16] aggregated a set of houses equipped with heat pumps and proposed several ways of achieving flexibility. This comprehensive study included a group of houses representing the Belgian residential building stock with the indoor temperature set to remain within the thermal comfort range at all times. Adhikari et al. [7] presented a framework to aggregate residential customers with a demand response aggregator. In this approach the energy flexibility of HVAC systems was deployed by communicating with an Internet-of-Things thermostat at each house. This approach was implemented in a simulation study on the aggregation of 200 houses, whose thermal parameters had been randomly assigned. Until now, studies of building clusters have not paid enough attention to the influence of occupancy and occupant behavior and are often performed for a single building archetype. The importance of these missing elements was pointed out by Goy and Finn [13].

For modelling building clusters, the archetype-based approach is a promising way to consider their diversity. Using this approach, the scaling-up of energy demand can be achieved by multiplying each archetype by the number of buildings represented by each archetype [17]. In considering modelling techniques, "white box modelling" is used to simulate different archetypes, while "grey box modelling", specifically RC models, are promising for the study of large-scale demand response [13,18]. RC models were used in [7] for the aggregation of 200 houses.

In terms of the above literature review, the first contribution of the present study is its data driven approach to estimating the energy flexibility potential of building clusters containing various archetypes during the time that they are unoccupied. The second contribution is the quantification of the uncertainty of the available energy flexibility for different scales of building cluster with different numbers of households. This approach is generic and scalable can be used to aggregate any number of dwellings. The value of the uncertainty quantification is in the planning of energy supply. A typical case is when a grid operator must have information on the reliability of deploying a certain number of households and buildings to achieve demand flexibility and balance the grid. Building upon existing state of the art research on energy flexibility in buildings, the present study goes further:

1. The presented model is generic and scalable, implying it can be used to simulate the flexibility of building clusters with three key features: varying the size of a building cluster, flexible combinations of occupancy pattern and building archetypes in each building cluster, and the control solutions applied to enable the provision of building flexibility. Previous studies in this field have tended to focus on only one or two of these three aspects, as discussed in the Introduction and Methodology sections.
2. Each feature of the model is comprehensively modelled and studied based on three different data sources, i.e. TABULA, Danish Statistics and Danish Time Use Survey. Models based on these three data sources are then closely integrated. This combination of data sources is new. On the one hand the study uses Danish information as an example for developing, validating and proving the value of this model; on the other hand, it allows for replicable research if data collected from other sites/countries are available.

A detailed description of the structure of the simulation platform and models is given in Section 2. In Section 3 the results of occupancy modelling and the energy flexibility of building clusters at various scales are presented. Section 4 contains a discussion and our conclusions.

2. Methodology

In this study, heat pumps are assumed to be used for space heating to provide energy flexibility. The following principles were applied:

- Heat pumps can be controlled for flexible electricity usage only during the time period when occupants are away, i.e. when the home is unoccupied. This is the worst case scenario, i.e. the minimum amount of flexibility offered by a dwelling assuming that end users do not allow any disturbance of their energy supply when they are at home, so external control can only be applied when they are not at home.
- The occupancy pattern is considered at the household level.

The energy flexibility is thus defined as the adjustable range of heat pump power during the period the apartments are unoccupied. Due to the stochastic nature of occupancy in households, the energy flexibility in this study is a probabilistic distribution with uncertainties instead of a determined number. The uncertainty of energy flexibility can be defined as the degree of dispersion of the distribution. Our hypothesis is "*The stochasticity of occupancy declines with the scaling-up of a building cluster, as does the uncertainty of energy flexibility*".

A data-driven approach was developed to model the energy flexibility of a building cluster, using MATLAB. The energy flexibility of a given building cluster is greatly influenced by the physical characteristics of the building and the occupancy pattern of individual households. A hybrid-model approach was used that consists of two parts: RC models for the buildings with each building represented as one RC mode, and occupancy models for buildings considering occupancy at