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Characterizing the energy flexibility of buildings and districts

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HIGHLIGHTS

- Energy Flexibility is defined as a dynamic function suitable for control.
- This definition leads to important and useful characteristics which are discussed.
- Furthermore, it defines a Flexibility Index both on individual and aggregated level.
- Based on this index a standardized method for labelling can be deduced.

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ABSTRACT

The large penetration rate of renewable energy sources leads to challenges in planning and controlling the energy production, transmission, and distribution in power systems. A potential solution is found in a paradigm shift from traditional supply control to demand control. To address such changes, a first step lays in a formal and robust characterization of the energy flexibility on the demand side. The most common way to characterize the energy flexibility is by considering it as a static function at every time instant. The validity of this approach is questionable because energy-based systems are never at steady-state. Therefore, in this paper, a novel methodology to characterize the energy flexibility as a dynamic function is proposed, which is titled as the *Flexibility Function*. The Flexibility Function brings new possibilities for enabling the grid operators or other operators to control the demand through the use of penalty signals (e.g., price, CO_2, etc.). For instance, CO_2-based controllers can be used to accelerate the transition to a fossil-free society. Contrary to previous static approaches to quantify Energy Flexibility, the dynamic nature of the Flexibility Function enables a Flexibility Index, which describes to which extent a building is able to respond to the grid's need for flexibility. In order to validate the proposed methodologies, a case study is presented, demonstrating how different Flexibility Functions enable the utilization of the flexibility in different types of buildings, which are integrated with renewable energies.

1. Introduction

The sustainable transition to a fossil-free energy system with a high penetration of energy conversion technologies based on fluctuating renewable energy resources, like wind and solar, calls for a paradigm shift in power systems [1,2]. Traditionally, power systems have been designed with centrally-situated large power generation units that are operated to meet the demand. However, to support the transition to a renewable energy system with intermittent and fluctuating power generation, a change is commonly suggested, where demand is adjusted to the available generated power [3,4]. Moreover, renewable energy generation is often locally situated, changing the present system from a unidirectional centralized system towards a bi-directional decentralized system with smaller units and multiple prosumers [5]. Such disruptive changes imply increased utilization of advanced control systems to enable flexible demand through demand response technologies and proper system integration [6]. The flexibility potential is already present (e.g., through heat storage [7]), and is further enhanced by advances and increased utilization of batteries [8]. Today, the use of model predictive control in buildings is seen as a strong opportunity to

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minimize costs, while still meeting the comfort requirements [9]. This control can be done either centralized by e.g., a grid operator (direct control), or decentralized by each building owner [10]. In this paper, the focus is on the latter type. The strategies used for defining the optimal controller can take a variety of parameters into account. For buildings the focus can be on energy efficiency, CO_2 efficiency, or minimizing the total cost [11], where trade-offs arise as a part of selecting the strategy. For example, a controller that is energy-efficient is typically not price-optimal given the energy markets and the energy-related taxes that exist today [12].

The building sector plays a key role in the future smart energy system as buildings account for approximately 40% of the global energy consumption [13]. Flexible buildings can provide grid services and thereby accelerate the transition to a low carbon energy system. The potential for using a building for demand response is defined as its energy flexibility [14]. The buildings' ability to provide energy flexibility is influenced by several factors [15]: (1) its physical characteristics such as thermal mass, insulation, and architectural layout, (2) its technologies such as ventilation, heating, and storage equipment, (3) its control system that enables user interactions; the possibility to respond and react to external signals such as electricity price or CO_2 factors, and (4) the occupants' behaviour and comfort requirements.

The energy flexibility potential can be found either by building *simulation* tools, i.e., deductively, or by use of experimental data, i.e., inductively by statistical *time series analysis*. Similar to a prediction of the energy consumption of a building, predicting the energy flexibility requires detailed dynamic modeling of a building's energy systems, including technical constraints, occupancy behaviour, and boundary conditions; see e.g., [16–18]. Using experimental data for estimating the energy flexibility of households with a price-responsive load was first suggested as a part of the FlexPower project [19]. However, the concept of controlling the energy balance in power systems using prices is not new, since it was first presented in [20]. In [21], the authors suggested the use of time series analysis tools to quantify the flexibility of buildings as a response to time-varying prices for the electricity using data from the Olympic Peninsula Project [22]. Similarly, in [23], a method based on inverse optimization was used to estimate the flexibility using real data. It was shown by [21] how the variations in penalties could be used to shift the load from peak hours to off-peak hours. The authors in [6,12] went a step further and demonstrated that the frequency and voltage in power grids could also be controlled by this method. However, they failed to specify which systems (e.g., buildings, districts, pools, etc.) are suitable for this approach.

Characterizing energy flexibility in a structural way is challenging as it involves many aspects [24]. A characterization of the energy flexibility and structural thermal energy storage is made in [25]. Here, the authors propose three characteristics: (1) available storage capacity, (2) storage efficiency, and (3) power shifting capability that reflects the relation between the aspects of power, duration and comfort constraints. Authors in [26], on the other hand, investigate the flexibility of a heat pump pool, and propose some characteristics; one example being the time until the electricity has returned to the baseline load. The drawback of the characterization methods in [25,26] is that they focus on specific characteristic numbers independently of each other. Furthermore, communicating the values of all these characteristics is complicated, and thus, there is a need for a simplified characterization that can take the dynamics of the system into account. The fact that these methods refer to a baseline load also makes them difficult to use in practice, where there is no baseline.

In this paper we propose a method to characterize the energy flexibility as a dynamic function, titled the Flexibility Function (FF). Unlike the bidding-based approaches that assume constant flexibility as described in [27,28], the dynamic nature of the FF enables the description of energy flexibility transients. Thus, it is useful even when the system is not in steady state, which is the case whenever energy flexibility has recently been utilized. The suggested method does not need any calculation of a baseline load. The FF can be determined either by simulation or by analyzing time series data. In situations where the FF is based on experimental data, it indirectly considers other factors such as heating equipment, usage, comfort and controllability. This generic energy flexibility characterization enables a comparison between systems with vastly different characteristics (e.g., an office building and a sewer system). It also enables the computation of the total flexibility when combining several systems. The suggested methodology for a dynamic characterization of the flexibility of e.g., a building, is designed such that it can be used for providing the energy system and the grid with ancillary services. Such services are given a high priority in the EU Winter Package [29]. In the linear case, the flexibility can be characterized using impulse response functions, step response functions, frequency response, and transfer functions - see also [30,31]. Consequently, the flexibility can easily be described using different approaches and characterized either in time or frequency domain. Since the intermittent energy sources may only partly be predictable, methodologies for energy demand management for dynamic systems under uncertainty must be established. It will be argued that the suggested dynamic description of the energy flexibility is designed such that it facilitates methods for providing grid services such as voltage control, load balancing, and other ancillary services. In this paper, we will focus on buildings, but the technology can be used for other types of flexible responses like waste water treatment plants [32] and supermarket cooling [33,34].

Based on the FF, a method for calculating a Flexibility Index (FI), which measures the reaction of a building or cluster of buildings to penalty signals like CO_2 intensity or control signals imposed by the grid, is also proposed. For instance, a FI of zero indicates that the building does not react at all, whereas a FI equal to 0.2 denotes that 20% of the penalty-related cost can be saved due to the smartness and flexibility of the building. This generic characterization of energy flexibility assumes that the system under consideration either contains a penalty-aware controller [6,11,35] or a manual response to variations in penalty signals like electricity price or CO_2 intensity (hereinafter referred as penalties) as described in [36]. The FI holds the essential information for particular applications of flexibility, and can be understood and communicated without technical insight in energy flexibility.

The paper is structured as follows: In Section 2 the novel idea of a FF is introduced along with the requirements for using it. Then, in Section 3 three applications of the FF is presented: (1) Quantitative description of energy flexibility, (2) Computing FIs, (3) Performing ancillary services. Next, Section 4 illustrates the concepts in a case study. Finally, Section 5 is a short summary and outlines plans for the future work.

2. Characterizing flexibility of penalty-aware buildings

This section introduces the novel idea of characterizing energy flexibility through a dynamic function, the FF, and the prerequisites for applying it. In this paper, we consider the building level. However, the methodologies can be applied to any energy-consuming system, e.g., a sewing system, a group of buildings, or a district. In many cases, it would actually be more optimal to consider a group of buildings, a smart district or a smart city, since the large scale offers solutions for energy production and storage, which may not be economically or practically suitable in the case of a single building. In fact, the district heating network in Denmark is a key element for the operation of the Danish power system that consists of more than 40% fluctuating wind energy [37].

2.1. Penalty-aware control and smart buildings

The methodology for characterizing energy flexibility presented in this paper are based on the general assumption that the system providing the flexibility is *smart* in a manner that it is able to respond to an external *penalty* signal. Penalty signals express the importance of a local