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Quantification of flexibility in buildings by cost curves – Methodology and application

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HIGHLIGHTS

- This paper presents a methodology for computing the flexibility of buildings.
- A cost curve shows both the amount and cost of the flexibility at a given time.
- A case study on an office building reveals the variability of the flexibility.
- Flexibility of heat pump systems is not free and the correct cost can be computed.

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ABSTRACT

The smart grid paradigm implies flexible demand and energy storage in order to cope with the variability of renewable energy sources. Buildings are often put forward as a potential supplier of flexibility services through demand side management (DSM) and distributed energy storage, partly as thermal energy. This paper presents a bottom-up approach for the quantification of this flexibility service. Cost curves are computed from the solution of optimal control problems with low-order models. These curves show the amount of flexibility and their associated cost. The method is generic and can be applied to heating, ventilation and air-conditioning (HVAC) services, thermal energy storage (TES) and local electricity production. A case study is performed on a monitored office building in Brussels, Belgium. The results reveal a large variation in both flexibility and cost depending on time, weather, utility rates, building use and comfort requirements. The study shows that for the studied day, flexibility is not for free. The mean flexibility cost has the same order of magnitude as the imbalance price in the Belgian power system.

1. Introduction

Due to the increased deployment of renewable energy systems with variable generation profiles, the need for flexible generation, flexible demand and energy storage increases. Simultaneously the electricity system evolves from a centralised to a distributed architecture with small-scale distributed generation (DG), distributed storage (DS) and controllable loads, often referred to as distributed energy resources (DER) [1]. This evolution, in combination with advanced ICT and control systems, leads to *smart grids* in which highly distributed loads are involved in power system control actions [2]. The benefits of increased responsiveness of the loads are described by Kirschen [3] and Strbac [4]. Buildings have a high energy demand and therefore they play a key role in the roll-out of these smart grids.

Buildings can offer frequency regulation or voltage control services to the energy and ancillary service markets through demand side management (DSM) [5–8]. Gellings [9] defines DSM from a utility perspective as "*the planning and implementation of those electric utility activities designed to influence customer uses of electricity in ways that will produce desired changes in the utility's load shape*". By simplifying the categories of DSM proposed by Palensky and Dietrich [10] we can say that DSM is composed of energy efficiency (EE) and demand response (DR). Flexibility is closely related to DR.

In the context of this article we define the flexibility of a building as *the ability to deviate from its reference electric load profile*. We will quantify this ability and express flexibility in kWh over a specified time span. This is explained in more detail in Section 3.1. Simultaneously we will compute the costs associated with the corresponding DR action and express it in € or €/kWh.

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Nomenclature

Symbols			
J	objective function	d	discomfort (thermal)
t	time	P	power
t_h	prediction horizon	E	electricity consumption
$F()$	system model	θ_{occ}	occupancy (0–1)
$g()$	equality constraints	γ	weighting variable
$h()$	inequality constraints	Φ	flexibility
u	control signal	Γ	flexibility costs
x	states	$\uparrow$	positive flexibility (more consumption)
y	algebraic variables	$\downarrow$	negative flexibility (less consumption)
w	disturbances	T	temperature
c	cost	C	thermal capacity
e	electricity	R	thermal resistance
g	natural gas	$\dot{Q}$	thermal flux

The aim of this work is to enable a quantitative comparison of the flexibility and corresponding costs between different buildings and groups of buildings. The developed metric can be used in the design process or when selecting a set of buildings to include in a DR scheme. It is not the intention to develop a methodology for operational decision making or real-time operation.

The first section in this paper gives an overview of how the flexibility concept has been treated in the literature. We show that there is no common metric or indicator to quantify flexibility. In the second section, a methodology is developed to quantify flexibility and the cost of the associated DR actions. This information is presented in a *cost curve*. The third section describes the application of the methodology on an office building in Brussels. The building and its HVAC system are presented and a low-order model is identified based on available monitoring data. In the last section we compute cost curves for different time spans, comfort requirements and system configurations and discuss the results.

2. Literature review

Flexibility is easy to define, but difficult to quantify. Petersen et al. [11] specify that "*The flexibility of a given system is a unique, innate, state-and time dependent quality. In conversation it is therefore sometimes said that flexibility is the ability to deviate from the plan. That characterisation of flexibility is very insightful, but it still leaves us with the problem of defining both the ability to deviate and the plan*". However, this is not sufficient: we also have the problem of defining the *cost to deviate from the plan*. Based on these costs, we could choose the most cost-effective ones to deliver the required flexibility for a given power system. Cochran et al. present a comprehensive overview of different techno-economic interventions to increase flexibility [12]. The authors mention that the relative costs are illustrative, confirming the need to quantify them in a reliable way.

There are different approaches to quantify energy use and costs. For a single building, generally a detailed model of the specific system or building is developed. The model typically takes electricity price profiles as input, and cannot take into account the different feedback mechanisms between load and centralised production. Many authors have studied load shifting control strategies in single building simulation or optimisation [13–16]. The reason for load shifting is a reduction of peak power, consumption, emissions or costs. Sreedharan et al. present a case study computing the cost-effectiveness of load-shifting for five buildings in California [17]. They conclude that the cost-effectiveness depends on site-specific characteristics, thus affirming the need for a more elaborated approach. These studies rarely define flexibility nor present a general methodology to assess the potential for different buildings. Six et al. simply define the flexibility of an appliance as the number of hours the operation can be delayed [18]. Flexibility is a key concept in the recently finished *LINEAR* project [19,20]. In *LINEAR*, flexibility is defined as "*the maximum time a certain power draw can be delayed or additionally called upon at a certain moment during the day*". This definition expresses flexibility in units of time and does not clearly quantify plan, deviation nor cost. In the EU FP7 project *ADDRESS* [21], an hourly flexibility index is calculated proportionally to the hourly load. The hourly load is computed according to the probability of use of the considered appliance during the day.

To quantify energy use and costs for multiple buildings, a top-down or a bottom-up approach can be chosen. The top-down approach mostly starts from the electricity generation park and models the demand by load curves. In these studies, the flexibility of the buildings is defined as the elasticity of the demand as a function of the electricity price [22,23]. In this approach, the detailed (thermal) dynamics of the buildings are neglected, and very general assumptions about the demand elasticity have to be made. It is therefore an input to the model, and not a result. A bottom-up approach starts from very simple and generalised models of the buildings and solves a unit commitment or (distributed) optimal control problem in order to optimise the operation of the full system [24]. This approach can be agent-based to allow operational optimisation in the context of energy markets and smart grids [25–28]. These methods assess the impact of load shifting on the total system, but do not quantify the amount nor cost of the flexibility of real buildings. Finally, the analogy between multiple buildings and virtual power plants (VPPs) can be made. The flexibility service that a VPP can offer is described by different authors [29–31]. Cochran et al. give an overview of methods to quantify flexibility [12] in power systems, but it is not applicable to individual buildings.

A calculation method to quantify the flexibility of buildings and its costs was not found in the scientific literature. This paper elaborates a generic method that results in cost curves. The cost curves allow to aggregate the flexibility of different buildings or DER systems in general. Moreover, the methodology is illustrated by application to a case of space heating with heat pumps in an office building.

The methodology developed in this paper was presented in a first version in De Coninck et al. [32]. A few months after this publication, Oldewurtel et al. published a similar idea [33]. This paper further develops on the methodology of the original work, integrates some of the ideas of Oldewurtel et al. and presents a case study on a real occupied building.