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ScienceDirect

Energy Procedia 91 (2016) 1053 – 1058

Energy Procedia

SHC 2015, International Conference on Solar Heating and Cooling for Buildings and Industry

A literature review of methodologies used to assess the energy flexibility of buildings

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Abstract

Due to the introduction of distributed renewable energy technologies with variable resource availability, the need of flexible electrical systems is evident. In general, flexibility is achieved from the supply side and often using carbon intensive energy generators. Therefore, improving the flexibility of the electrical system by taking advantage of renewable energy generation capacities and demand response measures in buildings is of major importance for a sustainable development. Control systems to implement these demand response measures need to quantify the flexibility of the respective buildings. Having this into consideration, this paper aims at presenting a literature review on methodologies to quantify the energy flexibility of buildings.

Peer-review by the scientific conference committee of SHC 2015 under responsibility of PSE AG

Keywords: buildings; energy flexibility; demand response; thermal energy storage

1. Introduction

The commitment with a sustainable development induced the introduction of greenhouse gas emissions limits, carbon taxes and ambitious renewable energy targets [1]. Achieving these targets through the use of renewable energy in buildings is seen as a short to medium term scenario. However, because the supply from renewable sources is governed by the availability of the respective primary energy source, there is often no correlation between production and consumption [2]. This mismatch is generally solved by introducing flexibility on the supply side often using carbon intensive generators. However, in order to meet sustainable development targets, cleaner solutions must be employed.

Having this into consideration, the flexibility of a building electrical system needs to be improved not only on the supply side but also from the demand side through the adoption of clean Demand Response (DR) measures. DR is not a new concept and it regards the modification of the usual consumption profiles normally as a reaction to

Peer-review by the scientific conference committee of SHC 2015 under responsibility of PSE AG
doi:10.1016/j.egypro.2016.06.274

different electricity prices [3]. Buildings are responsible for a large share of our energy demand, and therefore, may play a key role in improving the flexibility in the demand side of the entire energy system. In this context, the energy flexibility of a building is closely related with the DR measures which can be applied with the objective to make the building "deviate" from its reference load profile.

Although some research is available, a deeper understanding is required of the methodologies available to quantify the energy flexibility of buildings. This work is developed under the new International collaborative research initiative IEA EBC Annex 67 - Energy Flexible Buildings [4].

2. Energy flexibility

Although not specifically referring the flexibility, two main approaches are normally used to deviate the electricity consumption of a specific building from the normal plan: thermal energy storage and appliance operation shifting. The first approach is normally used to anticipate the energy consumption of a certain electrical device (e.g. air-conditioner, electrical water tank or heat pump), on the basis of the thermal properties of the device itself or of the respective building to reduce the consumption of electricity on later times, having into consideration the thermal comfort needs of the building's users. The second approach shifts the electricity demand to latter times through the control of some electrical devices (e.g. washing machines, clothes dryers, and dishwashers), to periods with lower electricity prices or with greater renewable energy generation.

3. Methodologies to quantify the energy flexibility of buildings

The development of methodologies to quantify the energy flexibility of buildings is normally affected by the definition of flexibility followed by the respective researchers. Currently, several different definitions of energy flexibility exist, each one distinct with its own methodology for quantification.

The methodology proposed by Six et al. [5] and improved by Thomas Nuytten et al. [6], considers the flexibility of a specific system as the ability to shift the consumption of a certain amount of electrical power in time. These studies quantify the flexibility of a specific system as the number of hours the electricity consumption can be delayed or anticipated. This methodology was tested to quantify the flexibility of residential heat pumps combined with thermal energy storage [5] and to quantify the flexibility of a Combined Heat and Power (CHP) system with thermal energy storage [6]. The flexibility profiles developed in the latter reference are shown in Fig. 1. The minimum and maximum curves refer to the accumulated energy provided by the CHP considering that the storage buffer is kept at minimum and maximum charge, respectively.

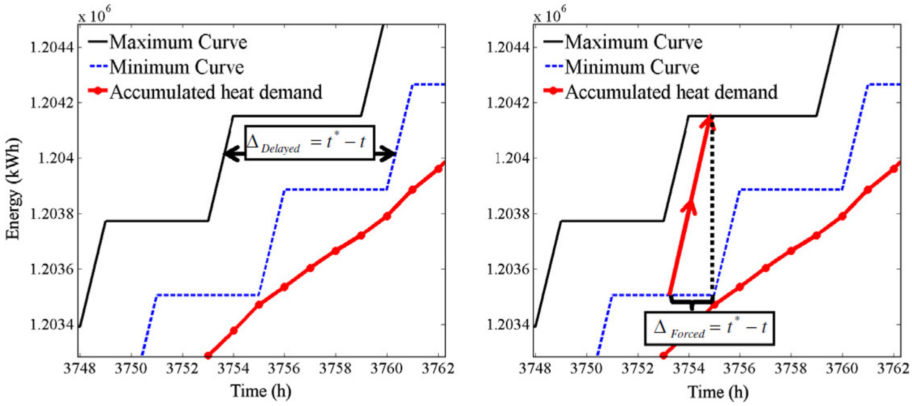

Fig. 1. Flexibility profiles (left) delayed operation; (right) forced operation [6].

The delayed operation flexibility corresponds to the amount of time $\Delta_{Delayed}$ the operation of the CHP can be postponed while the energy demand is met by the storage tank, Fig. 1 (left). The forced operation flexibility is quantified by the amount of time Δ_{Forced} the operation of the CHP can be forced while the excess heat produced is stored for later use, Fig. 1 (right). This methodology quantifies the flexibility of the analyzed system assuming that no flexibility was used before, resulting on the quantification of the maximum available flexibility.

De Coninck and Helsen defined flexibility as the possibility to deviate the electricity consumption of a building from the reference scenario at a specific point in time and during a certain time span [7][8]. Their work is focused on heating systems which use buildings' thermal properties to provide energy flexibility, their methodology being assessed through cost curves. The information regarding the potential for flexibility is achieved through three different control strategies and based on the electricity related costs. The first control strategy preserves the building's indoor temperature within the boundaries of the user comfort zone, while still minimizing the electricity costs associated with the operation of the controlled devices (considered the reference plan). The second and third control strategies minimize and maximize the energy consumption of the controllable devices during a time span in which the flexibility is computed (typically one to three hours), while maintaining the building's indoor temperature within the boundaries of the user comfort zone. The resulting three values of flexibility and costs are then used to build a cost curve as illustrated in Fig. 2 (left).

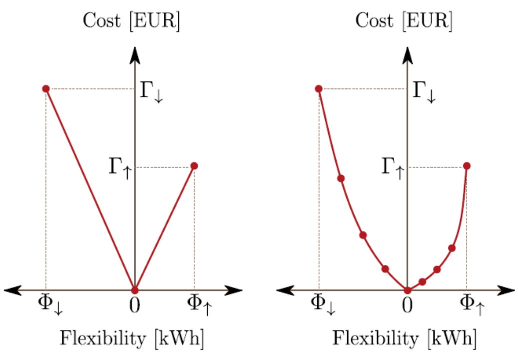

Fig. 2. Cost curves without (left) and with intermediate points (right) [8].

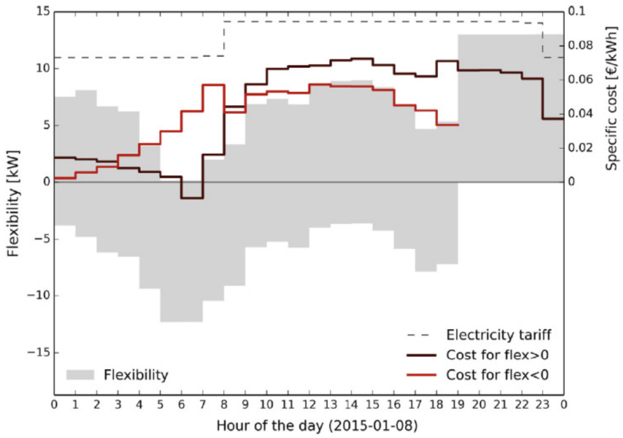

Fig. 3. Example of a time dependent energy flexibility profile [8].

A cost curve with higher resolution can also be achieved with this methodology by developing intermediate control strategies, Fig. 2 (right). Note that the point (0,0) regards the reference plan. An interesting characteristic of cost functions is that different curves can be aggregated to quantify the flexibility provided by a system composed by several subsystems. Additionally, if a cost curve is calculated at each time step, then the resulting information can be aggregated to obtain a time dependent energy flexibility profile as shown in Fig. 3.

Without specifically using the term energy flexibility, Oldewurtel et al. developed a methodology to quantify the energy shifting potential of a specific system (in practice these two terms refer to the same concept) [9]. They defined energy shifting potential ΔP as the amount of power a building can deviate from the baseline power consumption if needed. To quantify it, the authors use efficiency curves where the maximum possible power increase or decrease during a time interval is depicted against the power shifting efficiency. This efficiency refers to the ratio between the amount of power consumption modified during the mentioned time interval and the additional energy consumption of the system over a test period T. To develop the efficiency curves, e.g. Fig. 4, they perform distinct control strategies to assess the amount of power the building can deviate from the reference power consumption profile during a certain time span and the respective power shifting efficiency.

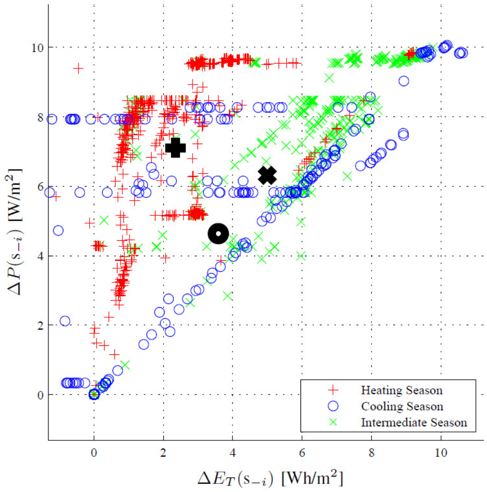

Fig. 4. Efficiency of power increase represented by the change in power consumption ΔP versus the additional energy use over the test period ΔET by season [9].

Under the scope of the LINEAR project, D'hulst et al. quantified the flexibility offered by five different types of domestic electrical devices (washing machines, dishwashers, tumble dryers, electric hot water buffers and electric vehicles) based on measured data [10]. LINEAR was a large-scale research and demonstration project conducted in Belgium focused on the introduction of demand response technology at residential level [11]. D'hulst et al. defined the energy flexibility of an electrical device as the power increases (P_{inc}) or decreases (P_{dec}) which are possible within functional and comfort limits, combined with how long these changes can be sustained. This definition supports the developed quantification methodology which is conceptually represented in Fig. 5. E_{max} and E_{min} represent the energy consumption profile when the power consumption is as early as possible and as late as possible, respectively. P_{ref} is the appliance's power consumption when the energy flexibility usage is started. When the flexibility of the appliance is used to increase or decrease the power consumption during a time interval ΔT, P is the resulting total power consumption of the appliance. Fig. 6 presents an example of the resulting energy flexibility profiles, concerning an extrapolation of the energy flexibility offered by dishwashers, tumble dryers and washing machines of the Belgian residential sector.

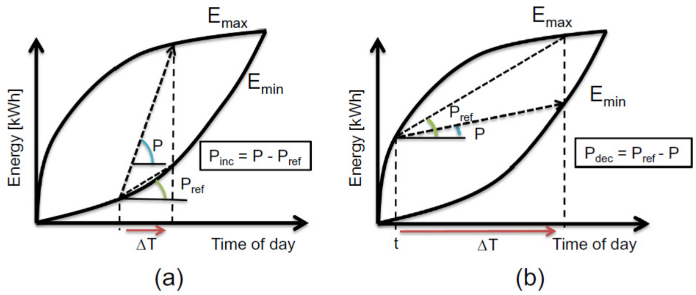

Fig. 5. Conceptual representation of the energy flexibility quantification methodology. (a) flexibility used to increase the power consumption. (b) flexibility used to decrease the power consumption [10].

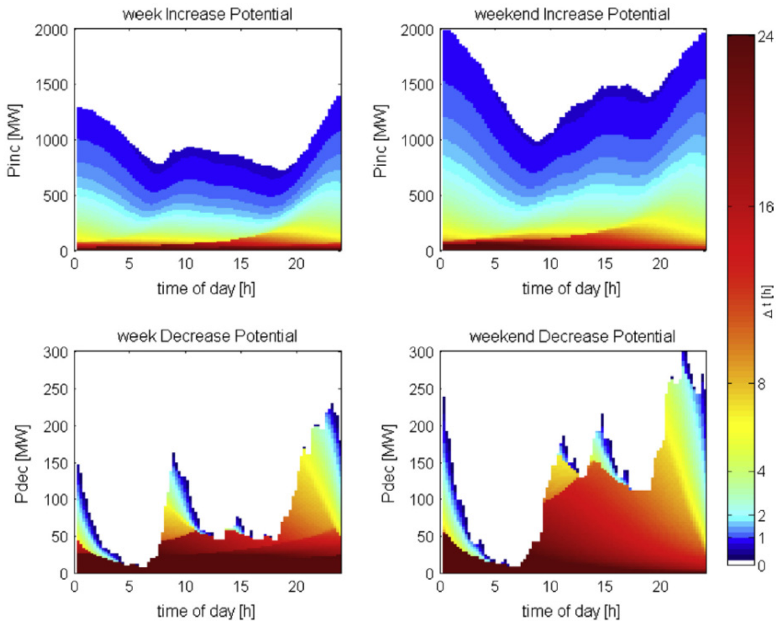

Fig. 6. Example of energy flexibility profiles [10].

4. Conclusions

A simplified literature review was conducted to summarize the existing methodologies available to quantify the energy flexibility of buildings. The analysis, conducted within the framework of the international collaborative research initiative IEA EBC Annex 67 - Energy Flexible Buildings, was able to identify several interesting approaches to assess the electric energy flexibility of buildings. It was found that energy flexibility is assessed on the basis of the deviation of electricity consumption under different scenarios assuming specific electricity related costs or thermal comfort schemes.

The conducted literature review shows that the methods aiming at assessing the energy flexibility of buildings are diverse and that their implementation can help matching energy demand with renewable energy capacities, although their impact needs further study.

Acknowledgements

The authors would like to gratefully acknowledge IEA EBC Annex 67 - Energy Flexible Buildings for providing excellent research networking. This study was made possible by doctoral grant SFRH/BD/87733/2012 issued by the (Portuguese) Foundation for Science and Technology (FCT).

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