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Building Energy Flexibility: A Sensitivity Analysis and Key Performance Indicator Comparison

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Abstract. Buildings are a key active element of the future Smart Grids with large shares of renewable energy, as they can provide flexible energy usage to help balancing power production intermittence. There is currently no consensus yet on how to quantify building energy flexibility. The various KPIs found in literature can be classified into 4 main categories: load shifting ability, power adjustment, energy efficiency and cost efficiency. Most of them use a reference scenario. Moreover, the envelope performance appears to be the most important parameter with regards to all aspects of building energy flexibility when using indoor temperature set point modulation.

1. Introduction

To mitigate climate change and reduce pollution, our societies must operate a radical decarbonisation of its energy systems and decrease their total energy need. Regarding the latter, the building sector has already been clearly identified as a major target since it accounts for one-third of the world's final energy use. Consequently, there was a significant improvement of the envelope's thermal performance and energy efficiency of the heating-ventilation-air conditioning systems in newly built and renovated buildings over the last decades. If the reduction of energy need for indoor space conditioning is a major achievement, buildings have been traditionally perceived as passive end-users in the energy system. However, in the context of future Smart Energy Grids, studies have shown that the building stock can be a key active element in integrating a large share of renewable energy sources (RES). The main drawback of RES is their intermittent power production and the difficulty to modulate it. In a RES-dominated energy grid, this might induce serious mismatch between instantaneous energy use and production which can severely compromise the stability of electrical and heating networks. To tackle that issue, demand-side management strategies have been developed for Smart Energy Grids to modulate the power needs of end-users and thus to counterbalance the irregularities of RES production [1].

Buildings can offer significant energy flexibility service. They can modify the pattern of their energy use by means of load shifting, peak shaving and valley filling (see Figure 1) to better fit with the RES production, but it is also possible to reduce costs associated with reinforcement of bottleneck weak points in the grid and operation of peak power production units. For instance, it is possible to delay some services provided by white-good appliances and shift in time the associated energy use [2]. The charging periods of electrical vehicles connected to buildings can be scheduled to avoid high power peaks and perform significant load shifting [3]. Electricity can be stored in the building's batteries [4]. In addition, buildings have a large potential for short-term thermal storage in hot water tanks (for space heating and/or domestic hot water) [5] and in the thermal mass of their indoor environment [6]. The latter can be a cost-effective heat storage solution by means of indoor temperature set-point modulation [7].

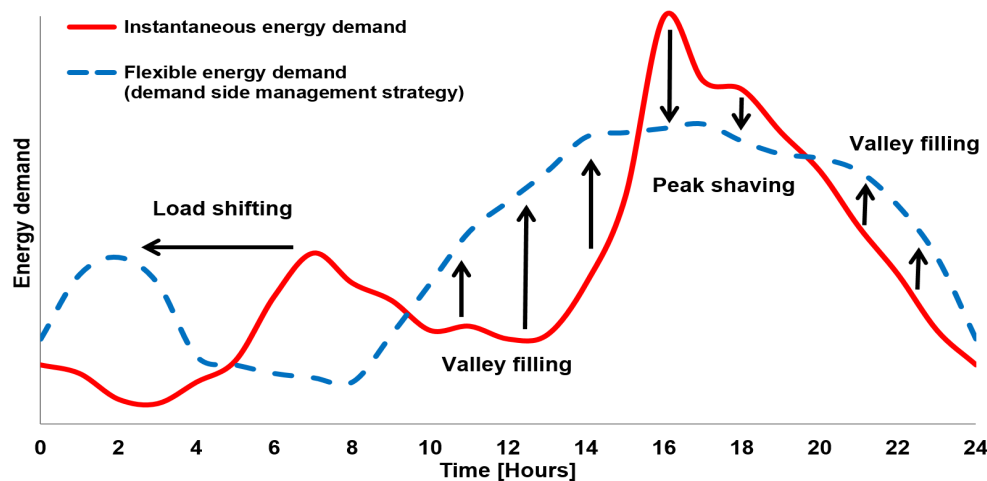


Figure 1. Example of demand side management / energy flexibility.

As the topic of building energy flexibility is gaining interest in the R&D community, many different assessment indexes have been created to quantify it. However, there is currently no agreement about the exact definition of building energy flexibility and how to quantify it. Tackling this issue by giving an overview and recommendations on this topic is one of the main goals of the IEA EBC Annex 67 Energy Flexible Buildings [8]. Nevertheless, energy flexibility is usually defined as “*the ability for a building to adapt its energy use profile according to local climate conditions, user needs and requirements of the grid (penalty signal) without jeopardizing technical and comfort constraints*” [9].

The aim of this article is to review and compare different building energy flexibility indexes found in the literature. In addition, a sensitivity analysis is conducted for the influence of the main building parameters on different aspects of energy flexibility when performing thermal storage in the indoor environment. The authors hope to provide better insight for the building community into how to assess energy flexibility and how to optimize the design of buildings for that intent.

2. Comparison of KPIs for building energy flexibility

The main goal of energy flexibility is to ease the integration of fluctuating RES. However, it can also be used to minimize energy costs, minimize CO₂ emission, avoid peak power demands, optimize usage of locally produced energy or prepare a building for a forecasted grid deficiency. Regardless of how one could define energy flexibility, it can be expected that it will not be a constant value in time because of its dependency to the interaction with the building’s indoor and external environment: building state, building storage level, local weather conditions, occupants’ behaviour, grid state, energy price, etc. However, the main aspects of energy flexibility can be defined as follows [8]:

- **Capacity:** amount of power change or shifted energy load.
- **Temporality:** duration of energy flexibility event; by how long the energy load can be shifted.
- **Efficiency:** peak shaving or load shifting efficiency, accounting for pre or post-rebound effects.
- **Cost:** Additional cost or cost savings generated by the activation of building energy flexibility.
- **Direction:** positive or negative alteration of the energy profile compared to non-flexible scenario; moving forward or backward in time energy load or power peak modulation.

In addition, one can imagine different types of penalty signal generated by the Smart Grid for demand side control, which can also be used in the cost estimation of the flexible activation: energy spot price, current CO₂ intensity of energy production, local state of the grid, marginal cost of production, etc.

A review of the current literature on the topic leads to several key performance indicators (KPI), each related to one of the specific aforementioned characteristics of energy flexibility. However, there is still no development of a holistic KPI integrating all aspects of energy flexibility. Although the different authors of the reviewed studies are using various forms of equation, naming and definition for their flexibility indexes, there are clear similarities between them.

Table 1. Classification of key performance indicators for building energy flexibility.

KPI category	KPI equation	Unit	Reference
Load shifting ability	$\frac{\sum_{i=1}^n \max(Q_{ref,i} - Q_{flex,i}, 0)}{\sum_{i=1}^n Q_{ref,i}}$	[-]	IEA EBC Annex 67
	$\left[\left(1 - \frac{\%High}{\%High_{ref}} \right) + \left(1 - \frac{\%Medium}{\%Medium_{ref}} \right) \right] \cdot \frac{100}{2}$	[%]	[7][15]
	$\frac{\int_{low} Q_{heating} dt - \int_{high} Q_{heating} dt}{\int_{low} Q_{heating} dt + \int_{high} Q_{heating} dt}$	[-]	[10][11]
	$\frac{\int_{Low} Q_{heating+cooling} \cdot dt - \int_{High} Q_{heating+cooling} \cdot dt}{\int_{Low} Q_{heating+cooling} \cdot dt + \int_{High} Q_{heating+cooling} \cdot dt} \times \frac{Q_{reference}}{Q_{flexibility_cases}}$	[-]	[11]
	$C_{ADR} = \int_0^{ADR} (Q_{ADR} - Q_{ref}) dt$	[Wh]	[12][13]
	$\Phi_{\uparrow} = E_{max} - E_{ref} \geq 0$ $\Phi_{\downarrow} = E_{min} - E_{ref} \leq 0$	[Wh]	[19]
	$\Delta_{Delayed,t} = t^* - t$	[hours]	[20]
	$\Delta_{Forced,t} = t^* - t$	[hours]	[20]
Power adjustment	$P_{difference} = P_{flexibility} - P_{reference}$	[W]	[11]
	$Q_{\delta} = Q_{ADR} - Q_{ref}$	[W]	[12]
	$\frac{P_{maxdaily}}{P_{continuous}}$	[-]	[14]
	$Flexibility(k) \triangleq P_f(e_k^u) - P_f(e_k^l)$	[W]	[18]
Energy efficiency	$\eta_{shifting} = \frac{-\Delta Q_{discharged}}{\Delta Q_{charged}}$	[-]	[10]
	$\eta_{ADR} = 1 - \frac{\int_0^{inf} (Q_{ADR} - Q_{ref}) dt}{\int_0^{ADR} (Q_{ADR} - Q_{ref}) dt}$	[-]	[12][13]
	$Overconsumption = \frac{E - E_{int}}{E_{int}}$	[%]	[17]
Cost efficiency	$\frac{\sum_{i=1}^n C_i \cdot (Q_{ref,i} - Q_{flex,i})}{\sum_{i=1}^n C_i \cdot Q_{ref,i}}$	[-]	IEA EBC Annex 67
	$FI = 1 - \frac{c}{c_0}$	[%]	[16]
	$\frac{P_{el,max} - P_{el,avg}}{P_{el,max} - P_{el,min}}$	[-]	[17]
	$\frac{flexibility_{PC} - flexibility_{PC,ref}}{flexibility_{PC,ref}}$	[%]	[17]
	$\Gamma_{\uparrow} = J_{c,max} - J_{c,ref} \geq 0$ $\Gamma_{\downarrow} = J_{c,min} - J_{c,ref} \geq 0$	[¤]	[19]

By studying the similitudes in definitions and equations of KPIs, the former can be classified in four distinct categories (see Table 1). One can see that most of the KPIs focus on the global load shifting ability (capability of the building to alter its energy use profile and shift power load in time to minimize the penalty signal) and the energy efficiency of such action (and its associated cost benefits or losses). In addition, the large majority of KPIs make use of a reference scenario without any energy flexibility activation. The KPI is thus often formed as a ratio or a difference between one particular aspect of the building energy flexibility during the reference scenario without demand side management and the scenario with demand side management. The use of a reference scenario is logical since energy flexibility implies some active effort from the building system to supply a service to the grid compared to a passive energy use profile with no influence from the grid.

3. Sensitivity analysis of building parameters on KPIs for building energy flexibility

This section presents the results of a sensitivity analysis concerning the influence of the main building parameters on different aspects of energy flexibility when using thermal storage in the built environment. The analysis is performed by means of indoor temperature set point modulation. 6 result data sets have been collected from different numerical investigations (see Table 2) and combined in order to obtain significant variations of the following building parameters and boundary conditions:

- **Type of building:** single-family house or office building.
- **Insulation level:** can also be denominated as building envelope thermal performance, since it includes windows performance and air infiltration.
- **Thermal inertia:** effective thermal inertia of the indoor environment.
- **Heating / cooling system:** the type of heating / cooling system installed in the building.
- **Control strategy / penalty signal:** different algorithms or rules are employed for the indoor temperature set point modulation controller. In addition, different penalty signals are used to activate the building energy flexibility.
- **Outdoor temperature.**
- **Solar radiation.**

Table 2. List of study case data sets used for the sensitivity analysis.

	Reference	Building type	Parameters being varied	Simulation period	Location
1	Johra et al. [7]	Single-family house	6	1 month	Denmark
2	Marszal-Pomianowska et al. [21]	Single-family house	6	1 year	Denmark
3	Liu and Heiselberg [11]	Office building	4	1 year	Denmark
4	Loukou et al. [15]	Office building	3	1 year	Denmark
5	Weiss et al. [22]	Single-family house	1	1 year	Austria
6	Le Dréau and Heiselberg [10]	Single-family house	2	1 year	France

Four result outputs are investigated here, which are the characteristics of the demand response of a building when subjected to an energy flexibility activation (for instance, increase of penalty signal), as defined by Junker et al. [16]:

- **A and B:** the total amount of energy decrease and increase, respectively, which represent the amount of energy shifted in time.
- **Δ :** the maximum change of power demand following the change of penalty signal.
- **β :** the total time of decreased energy demand after the increase of the penalty signal.

In addition, a load shifting ability index and an energy cost efficiency index are calculated for the entire simulation period of each data set (see KPIs of IEA EBC Annex 67 in Table 1). The sensitivity analysis is performed by means of consecutive Analysis of Variance (ANOVA) tests on linear regression models linking the aforementioned parameter inputs and result outputs.

Table 3. Sensitivity ranking of the main building parameters with regards to energy flexibility.

General ranking	Parameter	A	B	Δ	β	Load shifting ability	Energy cost efficiency
1	Insulation level	1	1	1	1	1	1
2	Thermal inertia	2	2	2	6	2	4
3	Heating / cooling system	5	5	3	5	3	2
4	Control strategy / penalty signal	4	4	5	4	4	5
5	Building type	3	3	4	7	5	3
6	Outdoor temperature	6	6	6	3	6	6
7	Solar radiation	7	7	7	2	7	7

Table 3 shows that the results of the sensitivity analysis clearly emphasize the preponderant influence of the building envelope performance on all the aspects of the energy flexibility. Secondly, the thermal inertia also has a significant impact. These results are in agreement with previous studies [7][10][17]. Those observations are in line with the current trend for improvement of the envelope thermal performance of new and renovated buildings. Therefore, buildings with energy efficient envelope and low energy needs for indoor environment conditioning will also be quite capable of providing energy flexibility with indoor temperature set point modulation. Moreover, larger thermal inertia, which can be appreciated for lessening episodic overheating in buildings, will also increase the thermal storage capacity of the built environment and thus improve its energy flexibility.

4. Conclusions

To establish reliable energy grid systems with a large share of RES, there is a crucial need to reduce the mismatch between power usage and intermittent production of renewables. To that matter, buildings are a key active element of the future smart grids as they have a large potential for demand side management and energy flexibility by means of load shifting, power peak shaving and valley filing. The building energy is usually defined as “*the ability for a building to adapt its energy use profile according to local climate conditions, user needs and requirements of the grid without jeopardizing technical and comfort constraints*”. However, there is no consensus yet about how to quantify this energy flexibility and its different aspects, and how to translate it into clear indexes. After reviewing the scientific literature on this novel topic, various KPIs have been found with a variety of notations and equations grasping one or two of the main characteristics of energy flexibility: capacity, temporality, efficiency, cost and direction. Those KPIs have been classified into four main categories based on definition and equation similarities: 1) load shifting ability, 2) power adjustment, 3) energy efficiency and 4) cost efficiency. Most of the KPIs use reference scenario and focus on load shifting ability or energy / cost efficiency of the flexibility action. The sensitivity analysis performed in this study can be of interest to building designers willing to improve the overall energy flexibility or a certain aspect of it. Similar to previous studies, this parametric analysis emphasizes the importance of the building envelope thermal performance and also the building thermal inertia. Design recommendations for maximizing all aspects of energy flexibility in buildings using indoor temperature set point modulation are, therefore, in line with the design recommendations for low energy buildings with high envelope performance.

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