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

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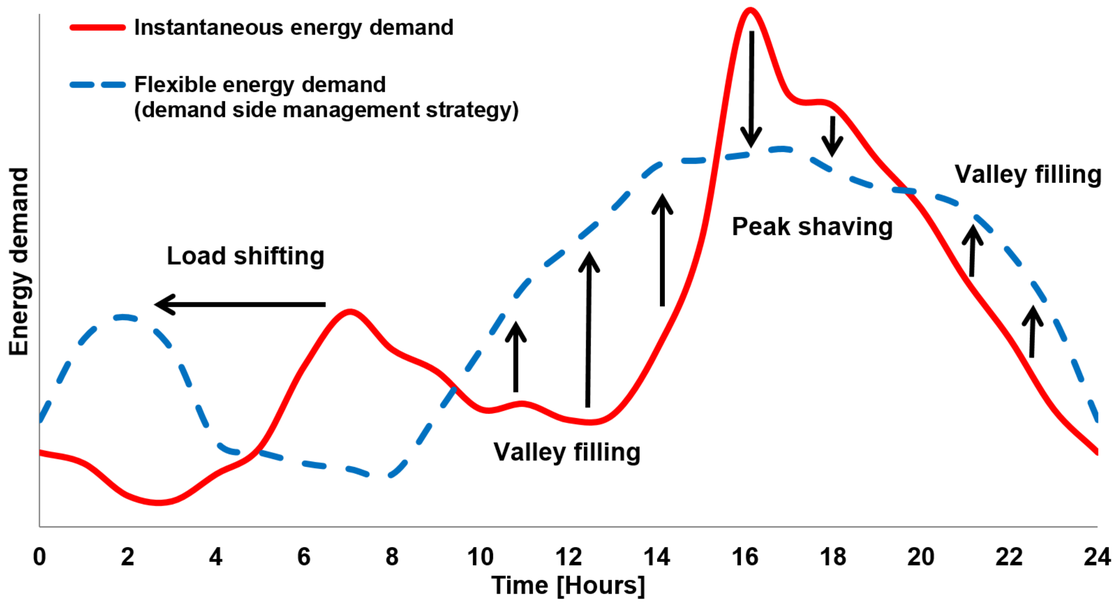
Introduction

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. 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*". However, there is currently no consensus yet on how to quantify building energy flexibility.



Example of demand side management / energy flexibility.

Objectives and methodology

The aim of this study is to review and compare different building energy flexibility indexes found in the literature. In addition, a sensitivity analysis is conducted on the data of 6 different numerical studies for the influence of the main building parameters on different aspects of energy flexibility when performing thermal storage in the indoor environment.

Comparison of KPIs for building energy flexibility

The main aspects of energy flexibility are as follows:

- **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.

KPIs from the literature can be classified into 4 main categories based on definition and equation similarities (see table hereafter). Most of them use a comparison to a reference scenario without flexibility control and focus on load shifting ability or energy / cost efficiency of flexibility actions.

KPI category	KPI equation	Unit
Load shifting ability	$\frac{\sum_{i=1}^{n} max(Q_{ref,i}-Q_{flex,i},0)}{\sum_{i=1}^{n} Q_{ref,i}}$	[-]
	$\left[\left(1-\frac{\%High}{\%High_{ref}}\right)+\left(1-\frac{\%Medium}{\%Medium_{ref}}\right)\right]\cdot\frac{100}{2}$	[%]
	$\frac{\int_{low} Q_{heating}\,dt-\int_{high} q_{heating}\,dt}{\int_{low} Q_{heating}\,dt+\int_{high} q_{heating}\,dt}$	[-]
	$\frac{\int_{Low} q_{heating+cooling}\cdot dt-\int_{High} q_{heating+cooling}\cdot dt}{\int_{Low} q_{heating+cooling}\cdot dt+\int_{High} q_{heating+cooling}\cdot dt}\times\frac{Q_{reference}}{Q_{flexibility\_cases}}$	[-]
	$C_{ADR}=\int_{0}^{ADR}(Q_{ADR}-Q_{ref})dt$	[Wh]
	$\Phi_{\uparrow}=E_{max}-E_{ref}\geqslant 0$ $\Phi_{\downarrow}=E_{min}-E_{ref}\leqslant 0$	[Wh]
	$\Delta_{Delayed,t}=t^{*}-t$	[hours]
	$\Delta_{Forced,t}=t^{*}-t$	[hours]
Power adjustement	$P_{difference}=P_{flexibility}-P_{reference}$	[W]
	$Q_{\delta}=Q_{ADR}-Q_{ref}$	[W]
	$\frac{P_{maxdaily}}{P_{continious}}$	[-]
	$\text{Flexibility}(k)\triangleq P_f(e_k^u)-P_f(e_k^l)$	[W]
Energy efficiency	$\eta_{shifting}=\frac{-\Delta Q_{discharged}}{\Delta Q_{charged}}$	[-]
	$\eta_{ADR}=1-\frac{\int_{0}^{\inf}(Q_{ADR}-Q_{ref}\,dt}{\int_{0}^{ADR}(Q_{ADR}-Q_{ref}\,dt}$	[-]
	$Overconsumption=\frac{E-E_{\text{int}}}{E_{\text{int}}}$	[%]
Cost efficiency	$\frac{\sum_{i=1}^{n} C_i\cdot(Q_{ref,i}-Q_{flex,i})}{\sum_{i=1}^{n} C_i\cdot Qref,i}$	[-]
	$FI=1-\frac{c^{1}}{c^{0}}$	[%]
	$\frac{p_{el,\max}-p_{el,avg}}{p_{el,\max}-p_{el,\min}}$	[-]
	$\frac{flexibility_{PC}-flexibility_{PC,ref}}{flexibility_{PC,ref}}$	[%]
	$\Gamma_{\uparrow}=J_{c,max}-J_{c,ref}\geqslant 0$ $\Gamma_{\downarrow}=J_{c,min}-J_{c,ref}\geqslant 0$	[¤]

Sensitivity analysis of building parameters on the KPIs

The sensitivity analysis performed in this study looks at the influence of the main building parameters on 4 characteristics of the demand response of a building when subjected to an energy flexibility activation:

- **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.

One can notice in the table below the dominant impact of the building envelope thermal performance and the building thermal inertia on all aspects of 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

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