|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **No.** | **Key Performance Indicator (KPI)** | **Unit** | **Standard/Initiative** | **Project** |
| 0.1 | Degree of Final/Primary Energy Self-Supply by RES | [%], [kWh/h] | SCIS, CITYkeys, SDG, ISO 37120:2018 | POCITYF, REPLICATE, MAtchUP, mySMARTlife, +CityxChange, SmartEnCity, ATELIER, syn.ikia, SPARCS, REMO URBAN, IRIS, Sharing Cities, triangulum, GrowSmarter, RUGGEDISED, RESPONSE, CITyFiED |
| 0.2 | Self Generation factor/Load Cover Factor | [-] |  | POCITYF, +CityxChange, syn.ikia, SPARCS, TRANS-PED |
| 0.3 | Self Consumption factor/Supply Cover Factor | [-] |  | POCITYF, +CityxChange, syn.ikia, SPARCS, RUGGEDISED, CITyFiED, TRANS-PED |
| 0.4 | Peak Imported/Exported Power (max, Pnet,max, and min, Pnet,min, values of the Net Energy Duration Curve) | [kW], [kW/m2] |  | syn.ikia, ATELIER, IRIS |

The literture review on the quantification of energy flexibily was complemented by a search conducted in Scopus database. It emerges that the topic is mostly addressed at the signle building scale through the definition of specific KPIs.

Table 2 summarizes the KPIs related to the energy flexibility of buildings defined within the relevant literature studies retrieved.

**Table 2: Overview of the energy flexibility KPIs proposed within some relevant literature experience.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **No.** | **KPI** | **Equation** | **Computational details** | **Ref.** |
| 1.1 | Self-consumption factor/Supply cover factor ( |  | • g: energy generation  • l: energy consumption  • t: time  • T: time period | (Salom et al., 2014) (Vanhoudt et al., 2014) |
| 1.2 | Self-generation factor/Load cover factor/Solar factor ( |  | (Salom et al., 2014) (Vanhoudt et al., 2014) |
| 1.4 | Grid feed in ( |  | (Finck et al., 2017) |
| 1.3 | Load match factor (fload), Load match index ( |  | (Voss et al., 2016) (Koch et al., 2012) (Salom et al., 2011) |
| 1.5 | Grid interaction index () |  | • SD: Standard deviation  • net grid: Energy exported to the grid minus the energy imported from the grid | (Salom et al., 2011) (Voss et al., 2016) |
| 1.6 | Loss of Load probability () |  | • *f(t)*: Percentage of time the local generation does not cover the load | (Salom et al., 2011) |
| 2.1 | Flexibility Factor -Costs |  | • L: energy consumption | (Le Dréau & Heiselberg, 2016) |
| 2.2 | Flexibility Factor ()-Emissions |  | • Electric power | (Péan et al., 2019) |
| 4.1 | Available structural storage capacity () |  | • : heating power during the ADR event  • : heating power during the ref. case  • t: time  • T: time period | (Reynders et al., 2015) |
| 4.2 | Storage efficiency () |  | (Reynders et al., 2015) |
|  | (Péan, Torres, et al., 2018) |
| 3.8 | Shifting efficiency ( |  | •“Heat charged”. Increased energy consumption in the ADR event compared to the ref.  •“Discharged heat”. Decrease in energy consumption in the ADR event compared to the ref. | (Le Dréau & Heiselberg, 2016) |
| 3.7 | Power shifting capability ( |  |  | (Reynders et al., 2015) |
| 3.1 | Added energy () |  | • : heating power during the upward flex. event  • : heating power during the ref. case  • : duration of the upward flex. event  • t: time | (Foteinaki et al., 2018) |
| 3.2 | Discharged energy () |  | • : heating power during the discharging period  • : heating power during the ref. case  • : duration of time after the end of the upward flex. event before ref. operation | (Foteinaki et al., 2018) |
| 3.3 | Curtailed energy () |  | • : heating power during the downward flex. event  • : heating power during the ref. case  • : duration of the downward flex. event | (Foteinaki et al., 2018) |
| 3.4 | Rebound energy () |  | • : heating power during the rebound effect period  • : heating power during the ref. case  • : duration of time after the end of the downward flex. event before ref. operation | (Foteinaki et al., 2018) |
| 1.7 | Self-consumption during DR action |  | • : onsite electricity generation  • : electric load during the flex. Event | (Bampoulas et al., 2021) |
| 4.3 | Storage capacity ( for the downward modulation, for the upward modulation) |  | • : electric load during the ref. event | (Bampoulas et al., 2021) |
| 4.4 | Storage efficiency ( for the downward modulation, for the upward modulation) |  | • = D | (Bampoulas et al., 2021) |
| 5.1 | Forced flexibility ( |  | • : Power required during the forced operation event minus the power required during the ref. case.  • t: time  • : time duration of the forced operation event | (Stinner et al., 2016) |
| 5.2 | Delayed flexibility ( |  | • : Power required during the ref. case minus the power required during the delayed operation event  • : time duration of the delayed operation event | (Stinner et al., 2016) |
| 2.3 | Available Electric Energy Flexibility (AEEF) |  | • : electric power during the flex. Event  • : electric power during the ref. event  • t: time  • T: time period | (Fitzpatrick et al., 2020) |
| 2.4 | Primary Energy Efficiency (PEE) |  | • : Primary energy consumption of the ref. case  • : Primary energy consumption of the flex. case | (Fitzpatrick et al., 2020) |
| 2.5 | Specific (Marginal) Costs (SC) |  | • : Difference in operating costs of cases ref. and flex | (Fitzpatrick et al., 2020) |

The indicators are grouped in several categories.

Category 1 summarizes the KPIs related to the grid interaction analysis. In this context, the KPI no.1.1 and 1.2, except for energy and storage losses, respectively reports on the degree of energy coverage with solar energy generated on site, while γs on the amount of local energy production self-consumed simultaneously by a prosumer building.

KPI no.1.3 quantifies the export of energy to the grid, no.1.4 the contemporaneity between self-generation and load in the building, no.1.5 the fluctuation of energy exchanges with the grid and KPI no.1.6 the loss of load probability, i.e. the probability understood as the expected number of hours, in the long run, for which the load is expected to be greater than the capacity of the generating resources.

If the flexibility objective is to maximize the self-consumption of energy from local RES or if the flexible behavior is aimed at providing services to the electricity grid, these KPIs allow an exhaustive interpretation and re-elaboration of the analysis results by providing concise information to stakeholders.

Category 2 is the sub-class of *Flexibility Factors (FF)*. The FFs no.2.1 and 2.2 formulate the more general concept of flexibility in quantitative terms with specific links to an objective function, which in most cases is operational costs and emissions. These KPIs investigate the distribution of the energy demand of the building in periods of high and low penalty (for example periods of high and low cost). *FFs* is variable in the range of [-1,+1]. A value of +1 would imply that all energy consumption occurs in the lp periods, while a value of -1 that the energy demand occurs in the hp periods. Therefore, higher factor values are representative of greater energy flexibility. Recently Péan et al. (Péan, Salom, et al., 2018), adapt the *FF (Costs)*, (Le Dréau & Heiselberg, 2016), to this objective, keeping its mathematical expression. Many authors use these *FFs* to quantify the shift of the load towards lp periods (Le Dréau & Heiselberg, 2016; Marotta et al., 2020; Péan et al., 2019; Péan, Salom, et al., 2018). However, as discussed in (Vigna et al., 2018) it explains how the load is distributed compared to the peaks but it doesn't give any information on how much load can be shifted

Category no.3, 4 and 5 includes sets of KPIs that refer to the application of ADR events of the SH system (Tab.3). Recently, Péan et al. (Péan, Torres, et al., 2018) proposed a reinterpretation of the formulation of (KPI n.3.2). Compared to the reference case, the KPI is calculated for the upward modulations of the SH set-point as the energy savings that occurs after the ADR event divided by the surplus energy supplied during the ADR event. For downward adjustments the KPI is interpreted as the expected increase in energy consumption that occurs at the end of the ADR event, as a rebound effect, divided by the energy savings that occurs during the ADR event. The results show ability of these KPIs (no.3) to highlight wasted energy: in some scenarios exceeds 100%, representing a very limited rebound effect, since in the reference case the energy consumption is disproportionate. In these regards, Foteinaki et al. in (Foteinaki et al., 2018), studying the potential of these flexibility events, define new indicators, KPIs no.4. Among the indicators, the *Added energy (Qadded)* (no.4.1) is defined. It represents the surplus of thermal energy supplied, with respect to the reference, during the ADR upwards event. While the *Curtailed energy (Qcurtailed)* (KPI n.4.3), is used to evaluate the reduction of energy needs during the ADR downwards event. KPIs no.3 and 4 overall, explicitly defined for ADR applications of the SH system, provide detailed information on the physics of the problem and to characterize the thermal response of the building. These KPIs do not allow per se a direct assessment of the effectiveness of the flexibility solutions used. Furthermore, as it refers to the need for thermal energy, they are not of direct use for grid operators and end users. Recently, Bampoulas et al. defined the KPIs no.4.1.1, 4.1.2 and 4.1.3 to quantify the effects of ADR actions in prosumer buildings. Based on the definition of KPI no.1.1, the authors define the *Self-consumption during the DR action*, the no.4.1.1. This KPI represents the percentage increase in energy demand satisfied by self-produced energy, during a DR action. Furthermore, starting from KPIs no.3.1 and 3.2 the authors extend the concept also to the heat storage by means of storage devices and electric vehicles, obtaining indicators no.4.1.2 and 4.1.3. These KPIs are also useful if ADR heating system events are implemented.

Among the applications of energy flexibility there is the flexible management of a thermal energy storage tank. In this context, the KPIs no.6 are defined to analyze the temporal aspects of flexibility. As discussed in (Stinner et al., 2016), (no.6.1) is representative of the period of time in which it is possible to keep the heat generator on (forced operation event), in order to accumulate the excess energy produced. Instead (no.6.2) is linked to the number of hours for which the thermal energy demand can be satisfied thanks to the energy discharged from the tank (delayed operation event). These KPIs do not provide information on the operational costs or emissions of the building, nor exhaustively on the effects on the interaction with the grid, focusing on the temporal aspects.

Recently, Fitzpatrick et al. define metrics no.7 to quantify the effects of applying Demand Response algorithms to improve the energy flexibility of buildings (Fitzpatrick et al., 2020). These indicators are related to the energy and economic aspects deriving from the implementation of the flexibility strategy. The authors suggest, to avoid ambiguity in the results of the metrics, the use of these KPIs when optimal control strategies, are used.

Overall, the literature review indicates that, in most cases, authors developing design approaches focused on energy flexibility, need to define appropriate methods of quantification or re-elaborate existing KPIs. This highlights the synergy between the modeling phase of energy flexible buildings and the development of flexibility KPIs and it is due to the great variety of aspects explorable.

Sector coupling efficiency

: non-shiftable load (appliences, lighting…);

: cooling e load;

: covarience of two vaiables;

: standard deviation.

P\_total = P\_lighting + P\_appli + P\_cooling

The index measures the linear correlation between non-shiftable load and shiftable load (thermal load). It is the ratio between the covariance of them and the product of their standard deviations; thus, it is essentially a normalized measurement of the covariance, such that the result always has a value between −1 and 1.

A collage of symbols

Description automatically generated

Bampoulas, A., Saffari, M., Pallonetto, F., Mangina, E., & Finn, D. P. (2021). A fundamental unified framework to quantify and characterise energy flexibility of residential buildings with multiple electrical and thermal energy systems. *Applied Energy*, *282*(PA), 116096. https://doi.org/10.1016/j.apenergy.2020.116096

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