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Review

Evaluation of methods for determining energy flexibility of buildings

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Abstract

The high rate of penetration of renewable energy sources leads to challenges in planning and controlling the production, transmission and distribution of energy. A possible solution lies within the change from traditional supply side management to demand side management. Buildings are good candidates for implementing a demand response model since they account for around 39% of global final energy use and are stably connected to all infrastructure networks. As a result, employing buildings as "players" in energy networks is considered now more than ever compelling. Recently, significant improvement has been denoted in the thermal efficiency of the building shell and the energy efficiency of the HVAC systems in new and renovated buildings. However, despite the reduction in energy demand regarding the space conditioning, buildings continue to be passive end users of the energy system. In order to ensure that they are capable of providing the necessary energy flexibility to balance intermittent energy production, a first step is to establish a formal, standard, and robust method of characterizing the energy flexibility provided on the demand side. Buildings can supply flexibility in a variety of ways, but there is currently no fixed and consistent method for quantifying the amount of flexibility a building can provide to future energy systems. In this paper, an overview of

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the literature on building energy flexibility will be offered, as well as an introduction to the concept of building energy flexibility and the methodologies used to define and evaluate it.

Keywords: Interactive buildings; Energy Flexibility; Demand Side Management (DSM); Building energy efficiency; Key Performance Indicators (KPIs)

1. Introduction

Global power usage has risen in recent decades in tandem with rising consumer demand for higher living standards [1]. This increase in global energy demand, combined with forecasts for reduced fossil fuel availability and indications for increased global warming effects have led to increased research interest in RES. Due to the inherent variability that defines energy sources such as wind and solar, the risk of energy network stability issues increases as RES become more dominant in meeting demand [2].

High generation and grid reinforcement costs, inefficient operation, and balancing and reliability issues are all rising concerns for electrical power systems [1]. To address these issues, significant expenditures will be required in the deployment of additional power generating units as well as the reinforcement of transmission and distribution networks [3].

The increased use of renewable energy sources has resulted in a rise in production at the distribution network level, while the entry and active engagement of consumers in the energy market necessitates a reassessment of how DSOs and TSOs operate and collaborate [4].

Traditionally, energy is centrally generated by generation units and delivered through transmission and distribution networks to customers in the classic energy grid paradigm [5]. In this situation, the energy flow is just in one direction. In today's energy networks, the penetration of renewable energy sources and their direct link to the distribution network has added the two-way flow of energy and information (Figure 1) [5].

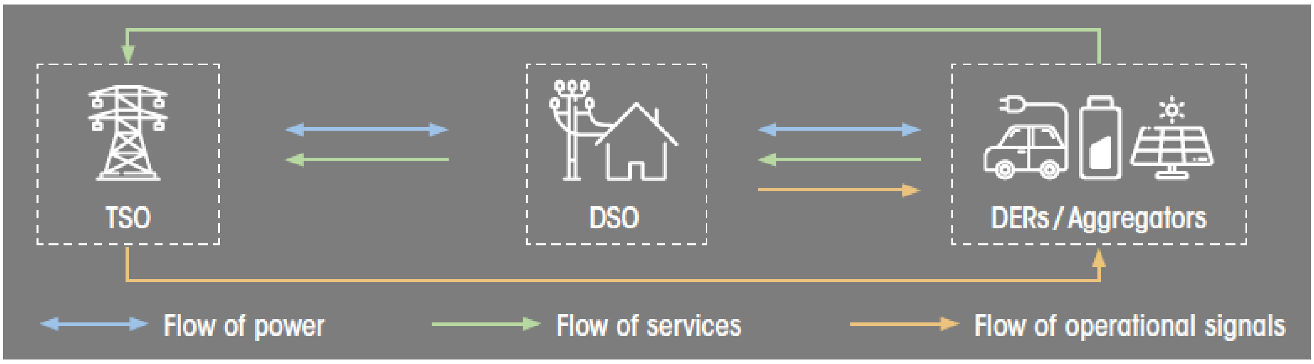

Figure 1 The flow of energy, services and information in future energy networks [5].

The demand for network stability reinforces the need to manage demand and to ensure flexible energy consumption. Buildings are supposed to play a significant role in this transformation by providing the energy system with their flexibility potential, either in the form of individual buildings or building clusters, to assist in fulfilling the demands of energy networks [2].

While buildings may offer flexibility in a number of ways, there is presently no standard technique for measuring the amount of flexibility they can contribute to future energy systems. Several review papers on building energy flexibility performance indicators have been published.

A study conducted by Reynders *et al*. 2018 [6], reviewed in several buildings, energy flexibility quantification methods emphasizing solely on thermal energy storage systems in residential buildings. Chen *et al*. 2018 [7], in their article, classified flexibility metrics and examined the methods for quantifying flexibility of building energy systems, but their review did not examine methods that consider the whole building's energy flexibility. Lund *et al*. 2015 [8] concentrated on the potential for supply and demand flexibility of different technologies in their research, but without providing clear indicators for assessing energy flexibility. A short review of energy flexibility quantification methods referring mainly to thermal storage and building appliances was presented by Lopes *et al*. 2016 [9]. Pean *et al*. 2019 [10] examined the application of control methods on heat pump systems for enhancing buildings energy flexibility. The acquired flexibility is evaluated using a variety of KPIs presented in literature. Vigna *et al*. 2018 [11] studied energy flexibility quantitative indicators and methods at the spatial scale of building clusters, while Kathirgamanathan *et al*. 2021, in their study, [12] examined the flexibility potential of the application of data-driven predictive control methods on buildings with minor focus on flexibility quantification metrics.

Current review papers cover a wide range of metrics, but none of them focuses on the characteristics of energy flexibility that the KPIs or metrics cover. This research gap needs further analysis, as researchers and practitioners in the energy flexibility sector can benefit from a study that focuses on classifying energy flexibility metrics according to a range of respective characteristics. Moreover, in the context of this review another innovation is that the range of established flexibility characteristics is expanded by adding a variety of smart building characteristics that are closely connected to and can help quantify flexibility.

Finally, the rest of the paper consists of four more sections. Section 2 gives an overview of the legislative framework regarding demand side management, buildings and their energy systems and the energy flexibility in future energy networks. Section 3 delves more into the topic of building energy flexibility, including an overview of energy flexibility definitions, building flexibility resources, control strategies, demand-side programs and load shaping methods. The literature review of energy flexibility characteristics and assessment and classification of metrics are introduced in Section 4, while Section 5 focuses on the conclusions, the present study constraints, and the future research possibilities.

2. Legislative Framework Regarding Buildings, Their Energy Systems and Demand Side Management

The EU wants to lead the transition to clean energy [13,14]. In this direction a target of decreasing GHG emissions is set by at least 55% by 2030 [15]. Simultaneously, EU seeks to improve energy efficiency, achieve worldwide leadership in renewable energy [14], and provide customers with reasonable energy supply conditions [13]. In this regard, it aspires to modernize the economy as well as create growth opportunities for all European citizens [13]. In 2018, the EPBD was revised, aiming to encourage smart building technology while improving consumers' involvement in future energy markets [16]. Consumers are anticipated to play a more active role if they have a range of energy suppliers to choose from, access to accurate energy price comparison tools, and the ability to sell self-generated power.

The idea and use of flexibility were regulated by the European Commission in 2017 [17], setting norms and duties for collaboration and data sharing between TSOs and other entities such as "aggregators". Aggregators are defined as "natural or legal persons combining multiple customer loads or generated electricity for sale, purchase or auction in any electricity market" [18]. Consumer's participation in the energy market was introduced in 2019 through [18,19], the foundations of a free energy market are laid, and the role of "aggregators" as an intermediary link between consumers and the wholesale market is recognized. In addition, the groundwork for the DSO's independence is being prepared. They are also obliged through directive movements calling for buildings to actively participate in the energy market and the right to sell self-produced energy, as long as network congestion is avoided. Furthermore, the legislation provides for the recruitment of demand management and energy storage technologies, as well as any other resource that will allow the transition to the new reality with the fewest feasible changes and/or expansions to the current energy network.

The development of an SRI will allow the evaluation of buildings in order to maximize their energy, as well as their overall, performance, while also ensuring that users' demands are met [16]. Future buildings will be able to adjust their main function in order to fulfill both users' needs (demand side) and network constraints (supply side). To achieve this aim, buildings should incorporate automations and energy monitoring technologies, as well as be able to provide relevant information to users about the economic benefits of energy conservation and altering the systems' function so as to meet the network's needs. The initial efforts to consolidate and promote the SRI index were taken in August 2018, with the release of a first technical research to establish the index's aims and features [20]. In January 2019, attempts were made for a comprehensive definition of the index in a second research based on the results of the first. This research revealed new ways for calculating the indicator and offered the framework that supports their function and describes them. In the same study, initial efforts were made to define the functions of the building systems and the measured parameters for its computation at the building level [21,22]. In December 2021 the SRI platform was launched. The platform further promotes the SRI and other associated best practices. It serves as a debate point for the main aspects of the SRI, as well as an exchange forum for all interested parties and EU countries [23].

3. The Concept of Energy Flexibility

3.1. Energy flexibility definitions

Various definitions of energy flexibility can be found in the international literature. A general definition describes flexibility as the ability to deviate from design load that characterizes a building or system [24]. In the context of Annex 67 of the IEA, energy flexibility is defined as "the ability of a building to manage its demand and production according to local climatic conditions, user needs and network requirements" [2,25].

In general, flexibility potential is mainly used to reduce energy costs or the cost of purchasing electricity from the grid. This is typically achieved by developing the ability to balance production and demand in real time, in order to maintain the stability of a network even in cases of increased penetration of renewable energy sources [26].

Eventually, energy flexibility can be defined as the ability of a building to react to some external stimulus, expressed as power or energy that can be shifted without compromising the comfort of the interior environment of a building [27]. Finding a standard way to correctly describe the form of those energy or/and power shifts is the main challenge while characterizing flexibility [27]. Flexibility aims at balancing production and demand. Therefore, when describing the power or energy shifting potential, the various objectives and constraints but also the optimal control strategies must be taken into account [28]. In order to achieve and evaluate the energy flexibility of a building a series of steps need to be applied. Firstly, the sources of flexibility are identified, then the building's loads are divided into two main categories, more "flexible" and less "flexible", and the appropriate control strategies that will allow the flexible operation of systems are selected. Finally, the key performance indicators that will allow the optimal evaluation of energy flexibility are defined and classified [29].

3.2. Energy resources of buildings

Energy flexibility in a building is typically achieved by disconnecting the power demand from the power supply, using some form of storage, or smart management of the operation of heating, cooling, air-conditioning, and lighting systems, shifting energy use from periods of high energy cost or network failure to periods of low energy cost [2]. Another approach used, is cutting off the least important loads, without having to restore them later [25]. According to Annex 67 the basic resources of energy flexibility of a building, are [2] the building thermal mass; the thermal energy storage; the fuel switch; the electricity storage; the local electricity production and the connection to energy grids.

The thermal mass of a building is used as a mean of short-term storage (from a few hours to a few days) of thermal energy and is utilized with the aim of load shifting when energy deficiency is observed [30]. The thermal mass includes the whole heat capacity of both the shell and the contents of a building (e.g., walls, floors, furniture, *etc.*). When utilizing thermal mass to achieve flexibility, special attention must be given to maintaining high thermal comfort levels within the building [2]. Achieving high comfort conditions within the build environment is one of the biggest challenges set not only by the legislation framework but also by the policy makers. Despite the intense research interest towards this direction, limitations and directives regarding the occupants' comfort and well-being are not yet clearly defined [31–33].

The storage of thermal energy is usually carried out through the storage of hot water for heating or/and DHW in water tanks [2]. Alternatively, PCM can be used as a storage medium instead of water [34]. The use of stored energy will enable load shifting through deactivation of the heating system or postponing DHW production for a certain time period.

Electricity storage is used mainly while applying load shifting strategies. In periods of low load demand the surplus electricity is stored, usually in the form of chemical energy (batteries) and is used in periods where insufficiency of load coverage is observed [35].

Fuel switch refers to the exploitation of the flexibility provided by the provision of energy services using different fuel each time depending on its price and availability. It applies to building systems with more than one power source installed [2].

Electricity generation concerns buildings with integrated systems for local energy production. Usually two types of technologies are considered, renewable energy systems (photovoltaic systems, micro-wind turbines) and small-scale power generation units (Cogeneration/trigeneration units) [36]. The RES systems provide flexibility by covering a portion of the building load, while the cogeneration and trigeneration units, which can offer sufficient controllability and minimal inherent variability, are utilized to maintain network equilibrium [36].

The building becomes more “energy flexible", but also "more resilient", through its connection to more than one energy networks (e.g., electricity grid, gas network, district heating network) [2]. The term “resilient” refers mostly to the thermal resilience of a building [37], except in the case of a building equipped with a gas CHP system, which can utilize the supply of natural gas for electricity generation and therefore becomes “energy resilient” [38].

3.3. Control strategies

It is important to adopt a type of control strategy in building energy systems in order to use a building and its systems to offer energy flexibility for the advantage of both customers and utilities [39]. The two major categories in which control strategies are classified, are RBC and MPC [10]. RBC is a basic heuristic technique that monitors the status of a parameter, for example temperature, and sets value limitations for it. When the limits are exceeded then the system responds changing its function according to the predetermined strategy [10,39]. MPC is a more complex method, which bases its function on modelling a building and forecasting its energy behavior [39]. In this case, the most efficient energy management strategy, usually results from solving an optimization problem with some constraints and a specific time horizon [10]. The implementation of any of the above control strategies, requires the existence of controllers installed in the energy system that we wish to control. The output of the control strategy is used as input of the controller. The final control is done through temperature or power regulation or by changing the operating profile of the system [10].

3.4. Demand Side Management programs

IBP and PBP are the two basic types of DSM programs [40,7]. Classic and market-based programs are the two types of IBPs. Consumers typically receive rewards in the form of points or a discount for participating in traditional programs, whereas participation in market programs typically leads to a cash reward, based on the amount of demand reduced during periods of high demand and/or reduced production (critical periods) [40,7]. PBPs apply to energy markets in which electricity price is not constant but varies depending on the wholesale price of electricity (dynamic pricing). Within the framework of PBPs application, high or low prices are provided during periods of high or low, respectively, while aiming on balancing production and demand [40,7].

3.5. Technical application of demand response

The technical implementation of demand response is accomplished through the use of two forms of control: direct control and indirect control [40,41]. Indirect control involves “aggregators” or utilities transmitting information on energy costs to consumers, who then decide whether or not to adjust their loads to save money. As communication is just an approach in this scenario, the aggregator cannot directly influence load demand; instead, it simply provides the necessary information and monitors any changes in load [40,41]. In the context of direct control, the "aggregator" or utility, whether it has the ability to request an increase or decrease in load during specific time periods or has direct control over individual loads. Consumers inform the "aggregators” about their decisions to shift their load so that they can estimate load demand and network status at a later time during direct control [40,41].

3.6. Load shaping methods

Peak clipping, increasing demand or valley filling, shifting load, strategic conservation, general load increase, and flexible load shape are the six fundamental strategies of load shifting (Figure 2) met in the international literature [42]. Peak clipping and valley filling are considered direct load management strategies, whereas load shifting is a mix of the two. Peak clipping is a reasonably simple and highly effective method of reducing peak power demands on a system, usually by direct control of customer loads via signals directed to consumer appliances [43]. Valley filling is another technique that focuses on decreasing the difference between maximum and minimum power demands [44]. During the implementation of valley filling the main objective is increasing demand during off peak hours which is usually accomplished by incentivizing customers to boost their demand [44]. Load shifting assumes the presence of regulated loads and is regarded as an excellent approach for preserving total energy balance as well as user comfort and well-being when each load is cut off and restored at a later time. Strategic conservation reduces overall seasonal energy consumption, mostly by eliminating wasted energy, and so improves system efficiency [45]. On the other hand, strategic load growth leads to an overall increase of seasonal energy consumption [45]. During a flexible load shape customers can purchase some power at lower than usual reliability levels. Depending on the real-time reliability conditions, the customer’s load shape will be flexible [46]. Because they include modifications to the whole shape of a load demand curve [42], the last three approaches need the use of intelligent control algorithms and are categorized as top-level control methods [47].

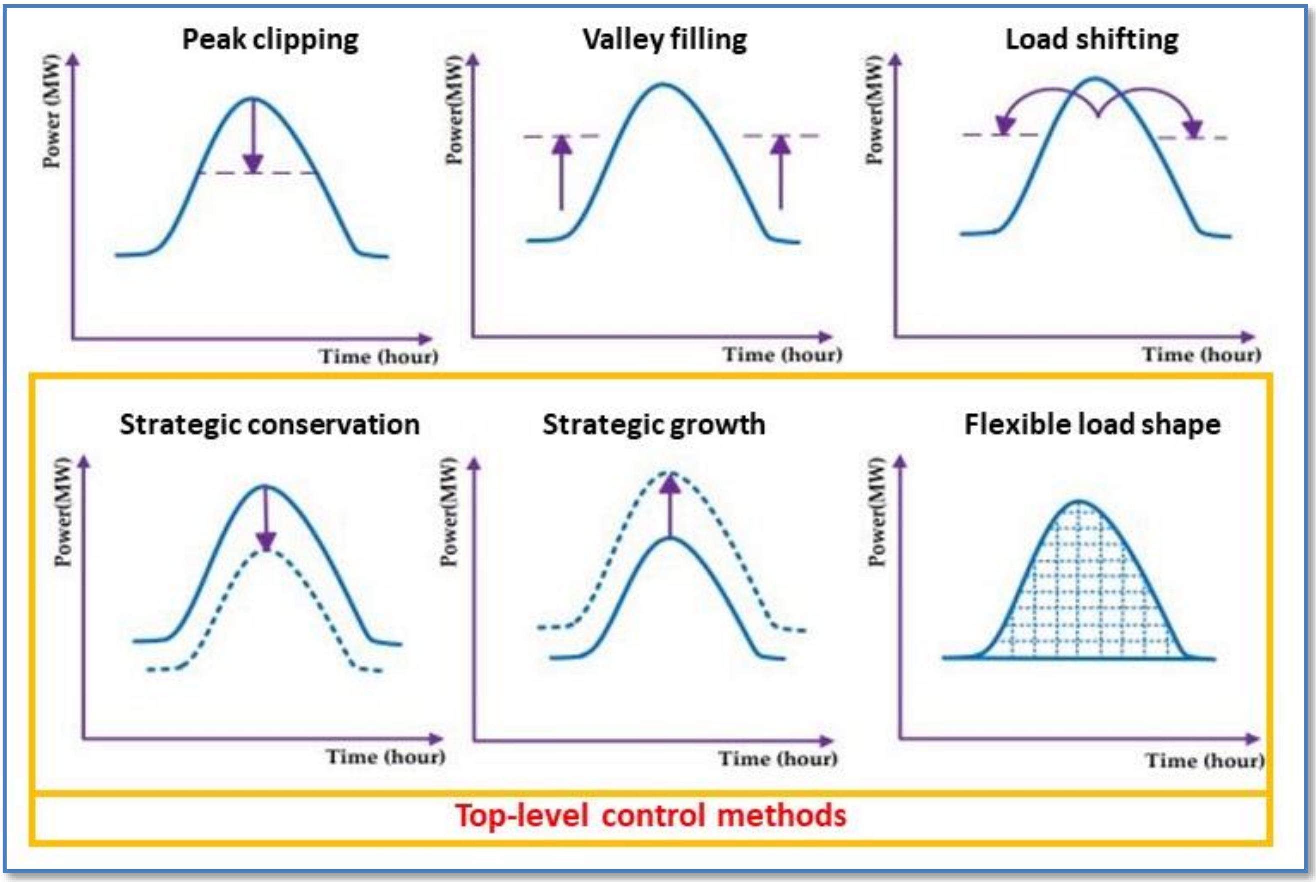

Figure 2 Load shaping methods [48].

4. Evaluation of Energy Flexibility Provided

4.1. Energy flexibility features

Time, capacity, and efficiency are the three major factors to consider when defining energy flexibility [2,49]. However, flexibility is influenced by a variety of factors (e.g., external environment conditions, building condition, user behavior, *etc.*), therefore more characteristics must be evaluated to draw safe conclusions about the potential flexibility of a building and its energy systems. Especially, flexibility should be studied as a dynamic phenomenon since one of its main characteristics is its changing nature [50]. The fundamental objective of energy flexibility is to support the seamless integration of renewable energy sources into energy networks. It can also help in improving network stability, lowering energy and CO_2 costs, and improving energy management at the building's level, as well as at the community level (microgrid) [51]. The indicators and methodologies to be utilized must generate meaningful information on energy flexibility both on the demand and production side. It is also critical to have well defined indications and procedures for assessing energy flexibility in the future energy stability system. A distinct context first utilized by Angelakoglou *et al*. (2019) to evaluate the performance of smart buildings, covers some more elements of energy flexibility and can help achieve the goal of accurately identifying and classifying flexibility indicators [52]. The application of this context will enable the assessment of flexibility as well as the overall performance from a more holistic perspective [29,52]. The main characteristics that can be used to classify flexibility indicators are, technical performance (e.g., energy consumption, load displacement potential, efficiency of on-site RES); environmental performance (e.g., reduction of CO_2 emissions); cost-effectiveness (e.g., reducing energy costs) and social performance (e.g., user comfort).

4.2. Indicators and methodologies for evaluating energy flexibility

Some indicators and techniques for assessing the potential of energy flexibility of buildings were denoted from the conducted in depth literature analysis based on research from the previous decade. Table 1 presents the indicators and methodologies identified in the literature, as well as the equations used to calculate them, the units of measurement, and the source from which they were obtained. The table's last column contains a brief description of the indicators and the methodology used, as well as the systems and buildings to which they were applied, but also comments on the outcomes of their application and the indicators' adequacy.

Table 1 Energy flexibility indicators denoted in literature.

Method/Equation	Units	Source	Description
Delayed operation flexibility/ $A_{Delayed,t} = t^{*} - t$	h	[53]	Both indicators quantify the flexibility of a system over time at which electricity consumption can be delayed or expected. Delayed operation flexibility refers to the amount of time that a CHP operation can be delayed, while load demand is covered by storage, and forced operation flexibility is the amount of time the cogeneration unit is in forced operation and at the same time continues to store energy. The main disadvantages of the method are the assumption that the system under study has not previously used part of its flexibility and therefore its maximum available flexibility is calculated, as well as its limited usability only in cases where some form of storage exists.
Forced operation flexibility/ $A_{Forced,t} = t^{*} - t$	h	[53]	
Flexibility Performance Indicator/ $FPI = \frac{1}{4}(p_1 \cdot t_{res}^{*} + p_2 \cdot \dot{P}_{res}^{*} - p_3 \cdot t_{rec}^{*} + p_4 \cdot \eta_{DR})$	-	[54]	The evaluation index summarizes 4 parameters for evaluating flexibility, response time (t_{res}^{*}), captive power ($\dot{P}_{res}^{*}$), recovery time (t_{rec}^{*}) and actual energy fluctuation (E_{DR}, used for calculating η_{DR} parameter). The index is calculated in dimensionless form. The flexibility assessment is completed by calculating the energy flexibility class of a building, as the ratio of the FPI to the FPI (FPI_{limit}) threshold. The value of FPI_{limit} results from the study of the building in stable conditions and considering the extreme case in which the thermal mass of the building is neglected

Method/Equation	Units	Source	Description
			and the heating/cooling load of the building is equal to the design load. The application of the indicator in a residential building with an installed air-water heat pump and a thermal energy storage system was studied. The index can give a relatively good picture of the flexibility that a building can provide as it takes into account a number of factors important for flexibility assessment. However, according to the study, its implementation can only be achieved using simulation tools to calculate FPI_{limit}. It would be interesting modifying it so that it can be applied to assess flexibility using real data from field studies.
Weighted Temperature Deviation/ $WTD_L = \int_{T_\infty < T_{min}} \lvert T_{op} - T_{min} \rvert dt$ $WTD_H = \int_{T_{ap} > T_{mex}} \lvert T_{op} - T_{max} \rvert dt$	K·h	[55]	The demand cover factor is defined as the percentage of electricity load that is covered by the photovoltaic and the supply cover factor is defined as the percentage at which the photovoltaic supply is covered by the electricity demand. To evaluate the effect of the application of control strategies on thermal comfort, they presented the weighted temperature deviation, which was set separately for the case where the temperature T_{op} exceeds the temperature of the upper comfort limit T_{max} and for the case where it is lower than the temperature of the lower comfort limit T_{min}. The indicator was used to assess flexibility of the thermal mass of a building, in the case of a building with a photovoltaic system and a heat pump installed.
Demand cover factor & Supply cover factor/ $\gamma_d = \frac{\int_{t_1}^{t_2} min(P_{PV}, P_d)dt}{\int_{t_1}^{t_2} P_d dt}$ *and* $\gamma_s = \frac{\int_{t_1}^{t_2} min(P_{PV}, P_d)dt}{\int_{t_1}^{t_2} P_{PV} dt}$	%	[55]	
Cost curves/ *flexibility [kWh] on horizontal axis, cost [€] on vertical axis*	€/kWh	[56]	The cost curve method is based on solving at least three optimal control problems. The first optimal control problem that is solved aims to minimize operating costs while maintaining thermal comfort. The second and third problems aim to minimize and maximize energy consumption for a specific time horizon for which flexibility is calculated, while ensuring that thermal comfort is maintained within the set limits. The resulting flexibility and cost values for each of the three cases are then used to plot the cost curves. A key advantage is its ability to be used in a wide range of buildings, climates and energy systems, as it is a generic methodology. Another advantage is the possibility of aggregating the cost curves of various subsystems. Finally, by calculating the cost curve for each time point, a flexibility profile in the form of a time series can be obtained. A major disadvantage of the indicator is the fact that the reference scenario concerns a building that is optimally controlled in terms of thermal comfort and energy consumption, and

Method/Equation	Units	Source	Description
			therefore any change in load always leads to higher costs than the reference costs.
Power Shifting Efficiency/ $\overline{PSE}(i) \quad := \frac{\Delta P(s_{-i})}{\Delta E_T(s_{-i})}$ $\underline{PSE}(i): \quad = \frac{\Delta P(s_i)}{\Delta E_T(s_i)}$	%	[57]	The methodology is used for quantifying the energy flexibility of a system. The power shifting potential ΔP is defined as the amount of power a building can shift ($P_i(s_i)$) in relation to the power consumption of the baseline ($P_i(s_0)$). The final indicator takes into account the costs due to the change of power and is defined as the ratio between the change of power consumption $\Delta P(s_i)$ to the additional energy use during the period under study $\Delta E_T(s_{-i})$. The index was used to assess the flexibility levels of a typical Swiss office building. The control of the operation of the building systems results from the solution of a control problem based on prediction models. Various control strategies are tested for which quantities previously mentioned are calculated.
Power Shifting Potential/ $\Delta P(s_i) := P_i(s_i) - P_i(s_0)$	kW	[57]	
Flexibility/ $Flexibility = \frac{p_{el,max} - p_{el,avg}}{p_{el,max} - p_{el,min}}$	%	[58]	The Flexibility index takes values from 0% to 100% and is maximized when all the energy required by the heating or cooling system of a building is used at the time of day when energy costs are minimized. The research studies the application of five control methods in various typologies of buildings equipped with heat pumps. The methodology can be easily applied to various typologies of buildings and energy systems.
Flexibility Factor/ $FF_S = \frac{\int_{DT} l(t)dt - \int_{NT} l(t)dt}{\int_{DT} l(t)dt + \int_{NT} l(t)dt}$	-	[59,60]	The energy shift flexibility factor (FF_S) is a metric that assesses a system's ability to adjust its energy usage. To maximize the utilization of on-site PV, the optimization tries to shift energy consumption toward daylight hours. When FF_S = 1, all energy consumption takes place during the day, when FF_S = -1, all consumption takes place at night. Savings on energy are computed by subtracting the consumption for the reference scenario from the building's actual consumption. Environmental savings are calculated by multiplying the difference between the reference and observed usage by the emissions mix of the grid power. Economic savings, take into account the earnings from the balancing market due to flexibility. The latter three indicators indirectly assess the provided flexibility.
Energy saving/ $\textit{Energy Savings} = \int_0^{24} P(t) - P_{ref}(t)dt$	kWh	[60]	
Environmental saving/ $\textit{Environmental Savings} = \int_0^{24} (P(t) - P_{Ref}(t)) * Mix(t)dt$.	kg CO_2	[60]	
Cost saving/ $\textit{Cost Savings} = E_{Flex} \cdot \epsilon_{use} + E_{FlexMap} \cdot \epsilon_{cap} + \int_0^{24} (P(t) - P_{ref}(t)) \cdot PVPC(t)dt$.	€	[60]	
Building Energy Flexibility Indicator/ $\textit{BEFI(Duration)} = \pm x(kW)$	kW	[61]	The BEFI indicates the ability of a building to shift its load demand for a specific period of time. BEFI can be considered as a status variable, which quantifies the available flexibility of a building and in ideal conditions can be utilized in real time by the building and the network to which it is connected.

Method/Equation	Units	Source	Description
			The automation system of a building with the use of appropriate software will be able to calculate the index in real time, so that the system administrator will be able to manage subsystems according to flexibility needs. According to the equation, + or – indicate the increase or decrease, respectively, of BEFI and "Duration" the duration of flexibility. The index uses a gray-box model (Resistance-Capacitance model) for the energy simulation and finally the calculation of the flexibility potential of a building. The results of the research showed small discrepancies between the simulation and the actual measurements, however the reliability of the model is not certain. In order for the model to be considered reliable and for the index to be able to produce robust results, tests must be performed on different building typologies, with different systems and different environmental conditions.
Reverse Power Flow/ $RPF = \begin{cases} 0, gen(t_n) - con(t_n) < 0 \\ \sum_{n\in\{1..N\}} [P_{gen}(t_n) - P_{con}(t_n)] \frac{t_{step}}{3600}, else \end{cases}$	kWh	[62]	The study introduces a virtual energy storage that utilizes models of thermal behavior of a building in which it integrates models of building energy systems and models of thermal comfort in an integrated optimization framework. Flexibility is exploited to improve penetration of RES. Four indicators which indirectly quantify the provided flexibility are implemented. These are, reverse power flow, self-consumption, self-sufficiency and thermal discomfort index.
Self-Sufficiency/ $Ss = \frac{E_{tot,\,RES} - RPF}{E_{cons}} \cdot 100$	%	[62]	
Self-Consumption/ $Sc = \frac{E_{tot,}\,RES - RPF}{E_{tot}\,,RES} \cdot 100$	%	[62]	
Thermal Discomfort Indicator/ $TDI = \sum_{n\in\{1...N\}} \left[\left(T_{BC}(t_n) - T_{OC}(t_n)\right) \frac{t_{step}}{3600} \right]$	ºC·h	[62]	
Storage Capacity/ $C_{ADR} = \int_0^{l_{ADR}} (Q_{ADR} - Q_{Ref}) dt$	kWh	[49,63]	The available storage capacity, expresses the amount of energy that can be stored to the thermal mass of a building during a DSM action, considering the dynamic conditions and taking into consideration the building's thermal comfort. Storage efficiency is defined as the percentage of energy stored in the building that can be used at a later time to provide flexibility and maintain thermal comfort. Both indicators relate mainly to the design phase and might be termed as building characteristics.
Storage Efficiency/ $\eta_{ADR} = 1 - \frac{\int_0^{\infty} (Q_{ADR} - Q_{Ref}) dt}{\left| \int_0^{l_{ADR}} (Q_{ADR} - Q_{Ref}) dt \right|}$	%	[49,63]	
Power shifting/ $Q_\delta = Q_{ADR} - Q_{Ref}$	kW	[49]	An indicator for real-time measurement of flexibility potential is the power shifting capacity, which expresses the amount of power shifting that can be achieved at a given time ($Q_\delta = Q_{ADR} - Q_{Ref}$) and the duration the shift can be maintained (t_δ). The indicators proposed in this study cover three aspects of energy flexibility, time, size and cost and were used to assess the flexibility offered by energy storage in the thermal mass of different building typologies.

Method/Equation	Units	Source	Description
			The fact that this methodology utilizes exclusively the input and output of energy in a system to quantify flexibility, makes it suitable for use in many different actions of energy demand response and storage.
Daily flexibility cost deviation/ $\delta C_{Flex} = C^{\alpha}_{Daily} - C^{ref}_{Daily}$	€	[64]	DR is evaluated by comparing the daily costs resulting from the solution of the new optimal control problems (C^{α}_{Daily}), with the daily reference costs (C^{ref}_{Daily}). Marginal costs can be defined as the ratio of cost fluctuations (δC_{Flex}) to the reduction of electricity consumption due to the demand response ($\boldsymbol{\delta E_{DR}}$). An indicator which is defined as the resulting change in primary energy consumption ($PE_{DR} - PE^{ref}$) is also used. The proposed indicators were used to assess the energy flexibility of a building in Northeastern Italy, which is equipped with a hybrid heating system consisting of an air-water heat pump and a gas-fired boiler, and a hot water storage tank for thermal energy storage. Various demand management methods are used and the effect of thermal energy storage on the amount of flexibility provided has been studied. The research is conducted at system level and therefore the building is used exclusively as a marginal condition of the optimization problem being solved. The indicators show quite good performance when evaluating the flexibility of the case study. A valuable addition would be the production and use of a detailed building model for the most accurate assessment of flexibility at both system and building level, and the study of different sizes of storage containers, as well as the control of the adequacy of indicators during the cooling period, with the aim of generalizing them.
Heat pump energy consumption variation due to demand response/ $c = \frac{\delta C_{Flex}}{\boldsymbol{\delta E_{DR}}}$	kWh	[64]	
Variation of primary energy consumption due to demand response/ $\delta PE = PE_{DR} - PE^{ref}$	kWh	[64]	
Flexibility (heating load shifting)/ $F = \left[\left(1 - \frac{\%\,High}{\%\,High_{ref}}\right) + \left(1 - \frac{\%\,Medium}{\%\,Medium_{ref}}\right)\right] \times \frac{100}{2}$	-	[65]	The index F tries to calculate the change in thermal loads of a building during periods of high energy cost, when the largest amount of energy use occurs during periods of low energy cost, i.e. the capacity to store energy passively in the building during periods of low energy cost, in order to save energy during periods of high energy cost. The index is a modified form of the one proposed by [60] to evaluate the effect of a building's thermal mass and indoor content on the energy flexibility that a building can provide. The index is applied for different cases of building shell and various heat emission systems.
Demand Response Potential/ $DR^{p}_{i} = \frac{\hat{P}^{base}_{i,h} - \hat{P}^{DR}_{i,h}}{\hat{P}^{base}_{i,h}}$	%	[66]	The study demonstrated the use of analytical and resistor-capacitor (RC) models for the dynamic thermal simulation of various buildings. A method was used to calculate the hourly demand response potential of the HVAC systems for various temperature

Method/Equation	Units	Source	Description
			regulation strategies. The equation calculates the load discharge potential ($\hat{P}_{i,h}^{base} - \hat{P}_{i,h}^{DR}$) in relation to the nominal energy consumption of each energy system ($\hat{P}_{i,h}^{base}$). Negative values indicate the ability to reject load, while positive values indicate the ability to increase load.
Time between max and min power/ $\frac{T}{2} = \frac{C_r}{B}\frac{TT}{T_{ref} - TT}$	h	[67]	The pulse integral (nominal power consumption) indicates the maximum tolerable energy level that can be added or subtracted from the rated power so that the average power is equal to the rated power. This flexibility indicator was proposed in the context of direct control, in order to allow the determination of the appropriate control signal to be sent to consumers according to their flexibility levels. The main advantages of the indicator is assuming the comfort of the indoor environment as a parameter of great importance and its applicability to most flexible loads, while the main disadvantage is the sub-optimization of the consumption profile in terms of cost minimization.
Power consumption increase/ $P_{inc} = P - P_{ref}$	kW	[27]	The study defined the energy flexibility of a device as "power increases" or "power decreases" combined with the length of time during which these changes can be maintained, while maintaining functionality and comfort. An upper E_{max} curve represents the energy consumption profile when most of the consumption occurs at the beginning of the time period, while a lower curve represents the energy consumption when most of the consumption occurs at the end of the time period. P_{ref} is the power consumption just before the start of flexibility use, P is the power consumption during flexible operation and DT is the duration of the flexibility operation. The difference between P_{ref} and P is the magnitude of the flexibility power (P_{inc} or P_{dec}), while combining the flexibility power with the DT time period, the flexibility in terms of energy is quantified. The indicators are used to quantify the energy flexibility provided by various electrical devices (plug loads), based on measurement data. The methodology bases its operation on the assumption that all flexibility is available and used over a specific period of time. It can therefore give an indication of flexibility potential but cannot be used as a tool for real-time programming and calculation of flexibility potential, as it does not take into account any effects from previous flexibility or system recovery actions.
Power consumption decrease/ $P_{inc} = P - P_{ref}$	kW	[27]	

Method/Equation	Units	Source	Description
Grid interaction indicator/ $PE_{grid} = STD\left(\frac{Pow_{mis,i}}{max[\lvert Pow_{mis,1}\rvert, \lvert Pow_{mis,2}\rvert, \dots, \lvert Pow_{mis,8760}\rvert]}\right)$	-	[68]	The grid interaction index is used to evaluate the grid stress induced by energy exchange fluctuation between a NZEB and the grid through evaluating and comparing grid friendliness. The grid interaction index, ranges from 0 to 1, with a lower value indicating higher grid friendliness.
Comfort indicator/ $PE_{comfort} = \sum\tau_i \begin{pmatrix} \tau_i = 1, \ ifCAP_{AC} < CL_i \\ \tau_i = 0, \ ifCAP_{AC} \geq CL_i \end{pmatrix}$	h	[68]	The comfort indicator primarily examines the total failure time during when the HVAC system is unable to meet actual cooling demand. The impact of system sizing on the time length of cooling supply insufficiency, which directly leads to thermal discomfort, is the focus of this index. In this study failure time is used to assess thermal discomfort.
Smart Built Environment Indicator/ $SBEI$	-	[69]	SBEI aids in the assessment of EU countries' readiness to migrate to smart buildings. The SBEI considers: "the energy performance of the building stock, the share of renewable energy, smart meter deployment, the development of a dynamic energy market, the improvement of demand response access, the roll-out of building energy storage, and the market penetration of electric vehicles" when determining how smart-ready the built environment is [11]. This indicator's specific applicability is for entire countries, although the features evaluated are adaptable to local clusters and can be used to assess flexibility at aggregator level.

The metrics are organized into categories based on the characteristics of energy flexibility that they address (Table 2) [29]. Indicators relating to one or two of the aforementioned sources of flexibility are found in the majority of research. In certain publications, indicators covering most elements of flexibility have been presented, but their robustness, quality, and accuracy of the data obtained during their use have not been confirmed [29]. As indicated in Table 2, most of the metrics analyzed are concerned with technical and economic performance, but a few are concerned with social performance, particularly the effects on the internal environment comfort. The technical performance indicators presented in [55] and [62] aim to describe the degree of utilization of on-site energy generation in relation to local energy demand, and can be referred to as load match indicators and PE_{grid} [68] shows the interaction with the distribution grid and can be considered a grid interaction indicator. Time, in the form of duration and capacity is investigated in fewer research studies, whereas environmental performance is studied in only one case. Moreover, only two surveys namely [54] and [69] presented a Holistic Approach Index, and the index was defined as a weighted average of individual flexibility indicators.

Table 2 Classification of energy flexibility indicators based on their characteristics.

Characteristics	Sources	Percent of Total Indicators
Time (Duration)	[53,61,67]	10.3%
Capacity/Storage	[49,63]	6.9%
Technical performance	[27,49,55–57,59–62,64–66,68]	44.8%
Environmental performance	[60]	3.4%
Social performance	[55,62,68]	10.3%
Financial performance	[56,58,59,60,64]	17.2%
Holistic approach	[54,69]	6.97%

5. Conclusions

For the adoption of high RES penetration in energy systems, optimizing the balance between production and demand is deemed essential. Buildings have this essential capacity and are capable of leading the clean energy transition. The measurement of the energy flexibility that buildings can provide is in that sense a prerequisite. As a general feature, when a structure can shift large amounts of energy over a long period of time, it is considered more flexible than a structure that can alter smaller amounts of energy over a shorter length of time [27].

According to the findings, there is no commonly accepted method for assessing energy flexibility. Furthermore, it is observed that there is no clear indicator that adequately characterizes it, taking into account all of the influencing factors.

The literature review conducted as part of this study revealed the presence of several indicators for assessing energy flexibility. Direct and indirect indicators are the two types of indicators that may be more easily used in this respect. Indirect indicators include those that measure the building's interaction with the grid, load balancing, energy efficiency, capacity, and thermal comfort of the internal environment, but do not directly assess energy flexibility. Furthermore, demand side management, the capacity to modify load, and the ability to absorb locally produced energy from the building are all tools that, when utilized together, may provide an integrated framework for evaluation.

The indicators were divided into groups based on the characteristics to which they may be related to. The categorization revealed that technical as well as economic and, to a lesser extent, social performance, are given high priority while measuring flexibility.

A variety of problems in recognizing and evaluating the energy flexibility of buildings have been highlighted, as a result of the current restrictions, which constitute topics of interest for future studies. When evaluating the flexibility potential of a building, it became evident that most of the studies do not take into account the flexibility of all building’s loads, but rather focus on thermal or on electrical ones. As a result, the first issue is to establish a specialized technique of modeling a building's flexibility, as it is currently essential to develop numerous models that analyze a building's entire flexibility. A second issue is determining the right criteria along with their weights, which will allow the development of a holistic approach indicators that offer a reliable profile of the available flexibility degree. The integration of quantified user comfort in the flexibility evaluation indicators is the final and most critical issue, as there are currently no indications in case of the influence of flexibility activities regarding comfort conditions in the indoor environment.

In this context, it should be emphasized that the integrated evaluation and realization of the goal of nearly zero energy buildings constitutes a multidimensional problem, rather than a one-dimensional requirement. In particular, all the bibliographic analyses indicate that evaluating the indoor environment conditions while taking into account users' comfort is needed to properly monitor the construction's operation, thermal comfort conditions, and management of the buildings' capacity.

Ethics Statement

Not applicable.

Consent for Publication

Not applicable.

Availability of Data and Material

Not applicable.

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Competing Interests

The authors have declared that no competing interests exist.

Author Contributions

All authors contributed to this research. In specific, Georgios Chantzis conceived, designed and performed the review, analyzed the data and wrote the paper; Panagiota Antoniadou analyzed data, contributed to writing and conceptualization, and edited the manuscript; Maria Symeonidou and Elli Kyriaki contributed to writing the manuscript and data analysis; Effrosyni Giama, Symeon Oxyzidis and Dionysia Kolokotsa supervised the manuscript and contributed to conceptualization and validation of the manuscript; Agis M. Papadopoulos contributed to the data analysis, conceptualization and validation , supervised and critical edited the manuscript.

Abbreviations

The following abbreviations are used in this manuscript:

BEFI	Building Energy Flexibility Indicator
CHP	Combined Heat and Power
DERs	Distributed Energy Resources
DHW	Domestic Hot Water
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operator
EPBD	Energy Performance of Buildings Directive
EU	European Union
FPI	Flexibility Performance Indicator
GHG	Greenhouse Gas
HVAC	Heating Ventilation Air-Conditioning
IBP	Incentive Based Programs
IEA	International Energy Agency
KPI	Key Performance Indicator
MPC	Model Predictive Control
NZEB	Nearly Zero Energy Buildings
PBP	Price Base Programs
PCM	Phase Change Material
RBC	Rule Based Control
RES	Renewable Energy Sources
SBEI	Smart Built Environment Indicator
SRI	Smart Readiness Indicator
TSO	Transmission System Operator

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