Bridging the Flexibility Concepts in the Buildings and Multi-Energy Domains

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Abstract. This paper aims to stimulate a discussion on how to create a bridge between the concept of flexibility used in power and energy systems and the flexibility that buildings can offer for providing services to the electrical system. The paper recalls the main concepts and approaches considered in the power systems and multi-energy systems, and summarises some aspects of building flexibility. The overview shows that there is romm to strengthen the contacts among the scientists operating in these fields. The common aim is to identify the complementary aspects and provide inputs to enhance the methodologies and models to enable and support an effective energy and ecologic transition.

Keywords: Ancillary services, Buildings, Flexibility, Grid services, Minkowski sum, Multi-energy, Operation, Thermal comfort.

1 Introduction

The concept of *flexibility* has been used in the engineering literature in the last decades, sometimes with different meanings. A contribution given in the Eighties defines *flexibility* as «*the capability of a system to maintain feasible operation over a range of uncertain/random conditions*» [1]. This definition contains three main aspects used to characterise flexibility, namely:

- Flexibility concerns the system *operation*, and as such depends on the *variable conditions in which the system undertakes its mission*, both internal (e.g., depending on the system constraints) and external (i.e., the variability of the environment outside the system).
- Flexibility is addressed by knowing the *feasibility* of the operational conditions. Feasibility can be determined by *establishing the operating regions of the system and their dependence on internal and external parameters*, variable in time. For this purpose, it is essential to define the operating point inside the operating region. When the analysis considers variations in time, the time series that contains the operating points becomes the operational *baseline* [2].
- Flexibility refers to the usage of the system in a short-term time frame in the future, and what will happen is subject to *uncertainty*. Thereby, *predictions and estimations* of the uncertainty referring to the future operation *have to be included in the flexibility assessment*. In this respect, the operational baseline and its uncertainty bands must be determined by resorting to predictions and progressively updated to provide a presumably effective expected reference.

In recent years, flexibility has become a keyword in various sectors. Each sector has developed some definitions, representations, and analysis tools almost independently. The number of publications referring to flexibility is already huge. Bridging the formulations and techniques of analysis becomes of interest, particularly in the sectors in which the interactions are becoming more intense. This is for example the case of the interactions between the building and the energy networks. There is an increasing interest in assessing the potential of the buildings for providing services to the energy networks (e.g., for electricity, gas, and district heating/cooling), also based on recent legislation and regulatory provisions that enable the demand side to play a more active role in the energy systems and the emerging energy communities.

On the side of the buildings, many aspects are addressed by the Energy in Buildings and Community Programme, with several documents available from the EBC Annex 67 [3], to show the energy flexibility that the buildings can provide to the energy networks. In the EBC Annex 67 framework, "*the Energy Flexibility of a building is the ability to manage its demand and generation according to local climate conditions, user needs, and energy network requirements*" [4].

On the electrical side, many definitions of flexibility contain elaborated descriptions, while others are shorter. Some examples are as follows:

- International Smart Grid Action Network (ISGAN) [5]: *«Power system flexibility relates to the ability of the power system to manage changes»*
- Electric Power Research Institute (EPRI), Flexible power operation [6]: «*Flexible power operation (FPO) is any mode of operation that is not baseload*»
- Council of European Energy Regulators (CEER) – Conclusion paper [7]: *«the capacity of the electricity system to respond to changes that may affect the balance of supply and demand at all times»*
- International Renewable Energy Agency (IRENA) [8]: *«the capability of a power system to cope with the variability and uncertainty that VRE (variable renewable energy) generation introduces into the system in different time scales, from the very short to the long term, avoiding curtailment of VRE and reliably supplying all the demanded energy to customers»*
- European Smart Grids Task Force Expert Group 3 [9]: *«the ability of a customer (prosumer) to deviate from its normal electricity consumption (production) profile, in response to price signals or market incentives*»
- International Energy Agency (IEA) [10]: *«the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales, from ensuring instantaneous stability of the power system to supporting long-term security of supply*».

The above definitions add further aspects to the flexibility concept, namely:

- The *balance between generation and demand*, including the time-coupling effect of storage, that has to be addressed within different timescales, from operation stability to security of supply [11].
- The *presence of economic incentives for changing the demand*, which enables the involvement of the consumers or prosumers by formulating specific incentives and considering the users' needs, especially regarding user preferences and thermal comfort depending on climate conditions.
- The *role of variable renewable energy sources* (RES), including the energy exchanges within energy communities and the possible curtailment in case of excessive production with respect to the grid limits [12].

This paper addresses the specific case of the interactions between the buildings and the electrical network (also indicated as the electrical *grid*). The focus is on the connection point of the buildings with the grid. A discussion on energy management aspects inside the buildings [13] is outside the scope of this paper. The gas and district heating/cooling network [14] are considered here, especially when heating/cooling are driven by electricity [15].

In particular, the interactions between buildings and electrical grid will be considered under two frameworks – demand response [16] and ancillary services [17] (or grid services). Participation of buildings to demand response programmes is still very limited [18], even though there is a remarkable potential [19]. The number of buildings is so high that even a small contribution by a relatively high number of buildings would be useful. Conversely, a response from most buildings could become excessive, so the careful design of the incentives included in the programme is crucial. From the grid side, the interaction is managed by the distribution system operator (DSO) for what concerns the technical aspects, the retailer with reference to the contract aspects of the electricity supply, and in case the aggregator, which manages a set of assets together to reach an overall size sufficient for being part of the power and energy management at the grid level. The grid could also be a microgrid, with the corresponding management and flexibility provision [20]. Aggregators manage a portfolio of end-users, activating possible smart contract options based on the definition of time-variable flexibility bands in which the aggregate flexible demand should vary [21].

The specific contributions of this paper are:
a) To provide information aimed at stimulating closer discussions among scientists working in the buildings and electrical systems domains.
b) To highlight the benefits of exploiting flexibility in multi-energy systems with grid-connected buildings.
c) To summarise the approaches and tools used for determining the contribution and profitability of multi-energy systems that provide grid services.

The next sections of this paper are organised as follows. Section 2 recalls the conceptual flexibility framework used in power and energy systems and summarises some aspects of building flexibility. Section 3 outlines some tools used for flexibility analysis in the electrical energy systems and multi-energy fields. The last section contains the conclusions.

2 Concepts and Operational Aspects of Flexibility

2.1 Flexibility in Power and Energy Systems

For power and energy systems, flexibility has been defined in different ways, referring to the generation side, the grid side, and the demand side [22]. The analysis tools have been formulated accordingly.
On the *generation* side, flexibility has been addressed by exploiting approaches taken from traditional problems such as *unit commitment* (i.e., the minimisation of the total cost of power generation for serving the demand in a given period through the appropriate scheduling of the generation units in pre-defined sub-periods) and *economic dispatch* (i.e., the determination of the power outputs of each scheduled generation unit in each sub-period). Stochastic optimisation techniques are needed to incorporate the effects of uncertainty. The relevant indicators are based on the maximum power (capacity), minimum stable generation output, and the up/down ramp rates of conventional generators.
On the *grid* side, flexibility has been defined as the ability of a power network to deploy its flexible resources to cope with volatile changes in the power system state during operation [23]. The increased uncertain renewable generation may cause higher operational risks of *congestion* (i.e., electric lines or transformers that exceed their technical limits). Congestions further increase operating costs and establish stricter limits on using the available flexibility resources from generation and/or demand.
On the *demand* side, flexibility can be achieved by using components able to adapt their operation and *shift* their consumption to different time intervals. Specific contributions come from individual and aggregate residential demand, thermostat-controlled loads, thermal energy systems, multi-energy systems, storage systems, electric vehicles, and other loads.

2.2 Flexibility in Power System Operation and Grid Services

In a power system, the possible flexibility services that can be offered to the electrical grid are determined by the needs of the power system itself in terms of power and energy during operation. Furthermore, sufficient reserves must be activated in case one or more power system components are unavailable. These services are also known as ancillary services by using the traditional nomenclature of adopted in the power system and in the electricity market*s*. In the traditional view of the power systems after the restructuring of the electricity business (at the end of the Nineties), the ancillary services were provided by generators only, in particular, from large generators. Successively, it has been recognised that some demand-side resources could be able to provide faster and more flexible responses than large generators [24]. For the electrical system, the relevant quantity at a given node is the *net demand*, that is, the difference between local demand and local generation. Hence, a demand reduction of a given amount and type in a given node is equivalent to a local generation increase of the same amount and type.
A summary of the main ancillary services is as follows:
o *Scheduling and dispatch*: the power produced in the system has to balance at any instant the power demand. Scheduling is carried out by preparing the units to use, while dispatch is used close to the real-time. Storage systems (if any) play either as

generators or additional demand during time, with the main limitation of the storage capacity available at a reasonable cost [25].

- *Frequency control* (or *regulation*): aims at maintaining the grid frequency close to the nominal frequency.
- *Reserves*: when there is a lack of production, more generators are called to provide additional power (or the power supplied by the generators already connected can be increased). The reserves are constrained by the time for entering into their operation mode. Among the operating reserves, the spinning reserves are already connected and can be dispatched quickly. Non-spinning reserves are already connected but need longer times to provide their service. Flexibility reserves have been introduced to respond to large fluctuations mainly due to RES. Replacement reserves are not connected and have to be connected by a specified time.
- *Reactive power and voltage support*: the electrical system node and its components are designed to operate under the nominal voltage. Any deviation from the nominal voltage should be compensated [26].

In a context with available resources and reserves, *operational flexibility* has been defined as the "*technical ability of a power system unit to modulate electrical power feed-in to the grid and/or power out-feed from the grid over time*" [27]. The operational flexibility in power systems is quantified by using four metrics [28] that consider the power provision capacity π (MW), the power ramp-rate capacity ρ (MW/min), the energy provision capacity ε (MWh), and the ramp duration δ (min). On these bases, the maximum available flexibility is defined by the limits on π, ρ and ε and can be visualised inside a *flexibility cube* [27]. However, the maximum available flexibility cannot be used at any time, mainly because of the time-related constraints. Thereby, the available operational flexibility that can be deployed depends on the time-variable constraints.

2.3 Flexibility in Multi-Energy Systems

Flexibility in Multi-Energy Systems (MES) is defined as the *technical ability of a system to regulate multi-energy supply, demand and power flows* subject to steady-state and dynamic constraints, while operating within predefined/desired boundary regions for certain energy vectors [29]. In a MES, there are different energy carriers and connections to the energy networks. Within the MES, the feasible energy flows depend on the specific constraints on the equipment (e.g., ranges of temperatures at which each equipment works). The constraints in the energy networks affect the available flexibility that can be obtained by adjusting the operation of the different equipment inside the MES. Once the initial operating point is defined, it is possible to calculate:

- the *upward flexibility*, given by the reduction of the electricity input from the electrical grid, depending on local generation increase or local demand reduction); and,
- the *downward flexibility*, given by the increase of the electricity input from the electrical grid, depending on local generation reduction or local demand increase).

In the presence of multiple energy carriers, the flexibility can be defined in different directions for each one of the energy carriers. For example, if the heat demand is kept unchanged (e.g., to maintain the same comfort level for the users), the electrical flexibility changes depending on whether to curtail or increase the electrical demand [30]. Moreover, changes in the user's electrical demand and the corresponding flexibility regions can be addressed by considering the timing at which the resources become available after being requested. In addition, it is important to consider that the feasibility ranges of some components can be limited, also with minimum technical limits, which may impact the construction of the overall feasibility regions of the MES [31].

The MES operational flexibility is strictly linked to the energy shifting capabilities
that appear inside the MES, which in turn depends on the existing one energy need with different equipment fed with different energy carriers (e.g., considering electricity and gas as substitutable resources [32]). This dependency does not guarantee perfect interchangeability among the components, because of different possible timings in the use of these components, for which the requested service cannot be provided in the same way. In general, the thermal dynamics are slower than the dynamics of the electrical systems. However, when the service is requested in a given time, depending on external aspects (such as the

user's lifestyle), some thermal systems (e.g., a gas boiler for heating water) could be faster than their electrical counterpart (an electric boiler).

2.4 Flexibility in Buildings Applications

The IEA EBC Annex 67 [3] indicates among the main aims the increase of the RES exploitation and the mitigation of the CO_2 emissions. It considers residential and non-residential buildings, addressing both new constructions and renovated buildings. In the latter case, the building renovation can include energy flexibility. Single buildings could have an energy demand too low for providing flexibility services to the grid. For this purpose, *clusters* of buildings are considered, either physically connected or commercially aggregated. The commercially aggregated buildings are owned by the same entity and are not connected to the same point of the Low Voltage distribution network. This situation, already existing in commercial activities, is also occurring with the energy communities. The aggregation of buildings is helpful to reach a sufficient impact to enter the market or provide grid services. The interaction of clusters of buildings with the electrical grid is an open research topic, especially when one or more buildings contain prosumers. The literature on multi-energy communities is making remarkable steps in this direction [30].

The IEA EBC Annex 67 defines the so-called *penalty signals*, as variable boundary conditions partitioned into high-frequency signals (e.g., ambient temperature, energy prices, user behaviour, and indications depending on the energy mix such as the amount of RES in the grid) and low-frequency signals (e.g., climate change, technology improvement, macro-economic factors and buildings use) [33]. The above notion of high and low frequency refers to the variations of the boundary conditions in the time scale of the energy usage [34], not to the notions of frequency used in the electrical systems. In fact, most electrical grid services (e.g., for frequency and voltage control) require remarkably higher frequencies than those indicated before. Thereby, the thermal inertia of the buildings makes the buildings unable to provide such fast services, because of the slow temperature variation and the energy payback effect that follows demand response actions [35]. Services with a longer time, such as load shifting and reserves, could be provided to some extent. Exploiting the thermal inertia of the buildings could provide an additional flexibility gain, provided that appropriate incentives are available [36]. However, the contribution of the thermal inertia heavily depends on the thermal characteristics of the buildings and the specific weather conditions [37], also considering the impact on the comfort level [38]. Assessing flexibility helps to define future strategies, so uncertainty has to be considered explicitly in the studies [39].

In the review presented in [40], most of the studies on energy flexibility refer to energy shifting. However, different aspects of energy shifting are considered, referring to energy price, electricity, energy infrastructures, and interactions with thermal comfort and external energy systems.

The determination of the available energy flexibility of clusters of buildings depends on the technologies and their control and the external conditions (climate, energy networks, markets) and the interactions with the occupants of the buildings. The flexibility of buildings is based on the definition of *flexibility functions* [41] by considering demand variations in response to a stepwise increase in the energy price [42]. Six flexibility characteristics have been defined in [43]. These characteristics include three time-based characteristics (i.e., the delay from the energy price increase and the appearance of initial effects on decreasing the energy demand, the time elapsed from initial demand decrease to the point of minimum demand, the and the duration from the initial demand decrease to when the demand reaches the level again before the price change). Two further characteristics are defined in energy terms, by considering the final demand level at the equilibrium point after the energy price variation and determining the total energy corresponding to the demand lower than the equilibrium point, and the total energy demand corresponding to the demand higher than the equilibrium point. The last characteristic is the maximum demand reduction with respect to the equilibrium point after the energy price variation. The use of the flexibility characteristics in a control system framework enables the exploitation of energy flexibility resources and the increase of the amount of RES that can be deployed [43]. These aspects are useful for DSOs and aggregators.

Absolute and relative grid support coefficients have been introduced in [44] and applied in [45] to four flexibility and storage cases in buildings (i.e., batteries, water tanks, thermal building mass, and fuel switch). Electricity consumption is assessed to identify when it occurs above or below the average electricity demand. Grid support coefficients lower than unity identify gridsupportive buildings. The results indicate that batteries are the most viable alternative for providing grid services, but also that, under the present electricity price variations, there is not enough reward to make these grid services solutions attractive for the user.

In a MES context, the potential of buildings to contribute developing grid services is based on the existence in the building of electrical devices or electrically-driven thermal components and systems, e.g., for electric heating, ventilation and air conditioning (HVAC), or electric cooking. In particular, the availability of electric heat pumps is a major asset for performing energy shifting to provide services to the electrical grid [35], especially if there is sufficient redundancy on the thermal side to avoid reductions in the thermal comfort of the occupants quantified in different ways [46]. Depending on the season, interactions with thermal energy storage could provide further inputs to increase flexibility [47]. To provide scheduling and dispatch ancillary services, possible strategies for curtailing HVAC demand are summarised in [48]. Dynamic models to address load shifting in HVAC that consider electricity consumption, variations in electricity prices, and indoor air temperature have been formulated in [49] and [50].

The provision of energy flexibility from buildings can be limited by (i) the age of the buildings (needing renovation), (ii) the limited revenues that can be given for providing grid services, and (iii) the need for installing or updating energy management systems for dealing with the communication requested to execute demand response programmes or to manage the interactions with the grid. These reasons partially explain why the building managers could consider that energy efficiency (handled with internal energy management systems, including RES and, in prospect, the charging of electric vehicles) is more important than providing flexible services to the electrical grid. Further insights on understanding the inefficiency of buildings in providing ancillary services are discussed in [51]. However, energy flexibility in buildings aimed at providing grid services may also be used to enable wider usage of RES [52], particularly photovoltaic systems [3]. Concerning RES, the main objectives refer to cost-effectiveness and the improvement of self-consumption (i.e., the percentage of the local RES generation used to cover the local demand) and self-sufficiency (i.e., the percentage of the local demand covered by the local RES generation).

2.5 Virtual Energy Storage

Virtual Energy Storage (VES) represents one of the most interesting bridge applications able to couple the built environment with the network infrastructure. In fact, any building presents a certain degree of thermal inertia: its exploitation allows to apply demand response actions by acting on thermal loads. It is worth noting that the model must include not only parameters of the built environment, but also comfort functions related to the occupants.

The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) classifies space thermal modelling into forward approaches and data-driven approaches [53]. The first family (also called white-box) of models has been classically developed for design optimisation. It is necessary to know the natural phenomena that may affect the system behaviour, as well as the interaction magnitude. However, these approaches do not require that the building is ready, hence can be used for preliminary design. On the other hand, data driven approaches include validated simulation models (based on approaches similar to the ones of the forward methods, but calibrated using real data), black-box models (i.e., empirical approaches, obtained by fitting historical data gathered from the system) and grey-box models (which include the physical description of the system and the parameters calculated through system identification methods).

Many past studies included VES as a flexibility asset in the electrical grid, for example, by introducing an equivalent thermal model based on temperatures (internal and external) and heat source (both artificial and natural) [54]. This model was used to develop an optimal load scheduling by considering the electricity prices and the energy balance. The building thermal mass can be exploited to operate a grid or a microgrid [55], introducing proper pre-heating/precooling schemes [40] acting as thermal load shifting for the benefit of the prosumer (comparable with or better than battery-based energy storage [56]). Another VES model, included into an electrical grid simulation framework, is based on the distinction between the thermal dynamic of the wall and the thermal dynamic of the space air, leading to a multi-resistance and multi-capacitance model [57].

3 Tools for Flexibility Analysis of Electrical Systems and MES

3.1 The Minkowski Sum

A key contribution to flexibility studies comes from the work of Hermann Minkowski on geometrical methods. In particular, the Minkowski sum (or Minkowski addition) has been used for adding two sets by taking one set and moving it along the borders of the other set. The Minkowski addition can be carried out progressively by summing up a new set to the result of the previous additions. In this way, it is possible to determine the boundaries of the aggregated feasibility regions by using Minkowski sums on polytopes [27]. The Minkowski addition is a powerful basic tool for constructing the MES feasibility regions starting from the feasibility regions of the individual MES components [29]. If one or more components have limited feasibility ranges, the result of their incorporation could lead to non-convex or even non-connected feasibility regions [31]. Possible *limitations of using* the Minkowski addition for calculating flexibility are discussed in [58], where a flexibility gap is determined by comparing the results of the Minkowski sum and of individual power profile summation.

3.2 MES Feasibility, Flexibility and Profitability Regions

Energy shifting is carried out by reducing (or increasing) the electricity exchanged with the grid, covering the shifted demand from fuel-based sources. In the provision of grid services from a MES, determining the possible reduction (or increase) of the electricity exchanged with the grid is the first step for understanding to what extent the MES is able to modify its internal energy flows. The maximum reduction (or increase) of the electricity exchanged with the grid has been indicated as *electricity shifting potential* [59], which is also the technical limit for providing flexibility. On the economic side, the changes in the energy flows needed to provide energy shifting are associated with extra operational costs for moving away from the baseline. If the baseline is optimal, the extra costs are always positive. Otherwise, some variations could lead to cost reductions with respect to the initial solution. The comparison between the extra operational costs and the possible revenues, carried out through profitability maps, identifies the profitability regions for which energy shifting may be convenient (considering the profits = revenues – costs), also finding out the most convenient solution [60]. If appropriate revenues do not compensate for the extra costs, there is no convenience in carrying out energy shifting.

3.3 The Energy Hub Model

An effective way to model a MES is to use the matrix representation formulated in the energy hub model [61]. This representation is based on an input-output model. All components are modelled by means of their efficiency matrix. The whole system is modelled through a coupling matrix that accounts for the individual efficiency matrices and the internal MES topology. A remarkable aspect is that the coupling matrix can be constructed directly by visual inspection of the MES topology and of the efficiency matrices, or by exploiting automatic procedures for analyses with non-linear [62] or linearised [63] models. Moreover, the dispatch factors representing the share of a given output that goes in different directions can be used as decision variables in an optimisation problem.

3.4 The Virtual Battery Model

In the flexibility studies, loads with particular dynamics have been represented by using a virtual battery model [64]. This model considers as parameters the energy capacity, the charge/discharge rates (which set up the power limits, starting from baseline conditions), and the self-discharging rate. The model has been applied to estimate the aggregate flexibility from thermostat-controlled loads (TCLs) [65] and has been enhanced in [66] by handling the effect of coupling constraints referring to the electrical grid to which the individual TCLs are connected. The model has been used to formulate multi-period optimal scheduling to exploit the aggregate flexibility from heterogeneous TCLs for providing multiple grid services and ancillary services [67].

In applications referring to buildings, the virtual battery model has been adopted for different purposes, e.g., to address the control of HVAC systems using a detailed building model [68] and to set up a unified approach for addressing flexibility of building loads and energy storage [69].

3.5 Power Node and Multi-Energy Node

The power node model [70] has been formulated as a unified approach for representing different units and their dynamics during the operation of a power system. The power node model enables the incorporation of energy storage and intermittent RES. The power node equation has been established with contributions that come from a baseline scheduling model, a model for schedule updates, and a model that addresses real-time control. Starting from the power node, a multi-energy node has been formulated in [29], which incorporates the basic energy hub model and adds the components that represent curtailments of demand or excess of production from multi-energy sources.

4 Concluding Remarks

The synthetic overview presented in this paper highlights that different definitions, approaches and tools are used to assess the potential of individual or aggregate buildings to provide services to the electrical grid in the specific domains. Some steps can be done to prepare a common field for discussions, for example, following the points outlined below. It could be helpful to check whether the effective tools and specific analysis techniques applied in different domains can be integrated for carrying out multi-domain assessments.

A network-based analysis is quite common in the electrical field, using the corresponding methodologies based on interconnected networks. The energy hub has been applied as a tool for hosting multi-energy modelling, again topology-based. Moreover, power system analysis is based on the network representation suitable to study fast dynamics close to real-time. Conversely, the traditional electrical modelling is less based on temperatures and details of the thermal modelling, such as phase changes and non-linearities due to the behaviour of the fluids. In this respect, even though the basic models have to remain closer to the specific domain, there are complementary contents to share, with synthetic but effective models to be exchanged among the scientists operating in the different disciplines.

In all domains, there are new aspects to integrate, concerning the incorporation of social and ecologic contents in the models, with the adaptation of the analysis techniques for considering, besides the uncertainty, the indeterminacy of the users' decisions. The social aspects are becoming more and more essential to address when dealing with the solutions for managing the interactions with the grid in the context of the energy communities, in which the energy management strategies may be affected by the personal decisions of final users who could not be willing to cooperate with the system. Moreover, the availability of huge amounts of data could lead to the increasing diffusion of data-driven approaches supported by machine learning. However, machine learning alone cannot solve all situations. The role of the domain experts remains crucial for checking the data to use and interpreting the results.

Other new contents to include depend on the expected diffusion of electric and hybrid vehicles, further increasing the demand in the distribution grids. The challenge is not only the management of the battery charge (and discharge, in case of active vehicle-to-grid options that could also lead to shaving the peak of the electrical demand). The key point is integrating the presence of electric or hybrid vehicles within the multi-energy management inside the buildings.

On top of the previous aspects, the economics of the interactions between buildings and the grid will have to be developed by formulating smart contracts with sufficient revenues and moderate risks to become attractive for the prosumers. In this evolving scenario, the scientific communities are expected to follow the common aim of identifying the complementary aspects and provide inputs to enhance the methodologies and models used for creating a common language and improving their algorithmic tools. Flexibility assessment is a solid common ground for developing consistent experiences, and will represent one the effective way to guarantee the implementation of the energy transition multi-secor policies.

5 References

1. Swaney R.E.; Grossmann, I.E.: An index for operational flexibility in chemical process design. Part I: Formulation and theory. AIChE 31 (4), 621–630 (1985).
2. Lin, Y.; Barooah, P.; Mathieu, J.L.: Ancillary services through demand scheduling and control of commercial buildings. IEEE Trans. Power Syst. 32 (1), 186–197 (2017).
3. Energy in Buildings and Community Programme, EBC Annex 67, [Online] http://annex67.org
4. Østergaard Jensen, S.; Marszal-Pomianowska, A.; Lollini, R.; Pasut, W.; Knotzer, A.; Engelmann, P.; Stafford, A.; Reynders, G.: IEA EBC Annex 67 Energy flexible buildings. Energy and Buildings 155, 25–34 (2017).
5. Hillberg, E. *et al.*: Flexibility needs in the future power system – Discussion paper. ISGAN Annex 6 Power T&D Systems, 2019.
6. EPRI: Flexible Operations Program. [Online] https://www.epri.com/portfolio/programs/106194, 2021.
7. CEER Distribution Systems Working Group: Flexibility use at distribution level - A CEER conclusions paper. CEER C18-DS-42-04, 17 July 2018.
8. IRENA: Power system flexibility for the energy transition: part 1, Overview for policy makers. International Renewable Energy Agency, Abu Dhabi, 2018.
9. European Smart Grids Task Force - Expert Group 3: Demand Side Flexibility - Perceived barriers and proposed recommendations, Final Report, April 2019.
10. IEA: Status of power system transformation 2019: power system flexibility. International Energy Agency, May 2019.
11. Zhou, Y.; Cao, S.: Quantification of energy flexibility of residential net-zero-energy buildings involved with dynamic operations of hybrid energy storages and diversified energy conversion strategies, Sustainable Energy, Grids and Networks 21, 100304 (2020).
12. Li, H.; Wang, Z.; Hong, T.; Piette, M.A.: Energy flexibility of residential buildings: A systematic review of characterization and quantification methods and applications, Advances in Applied Energy 3, 100054 (2021).
13. Li, R.; You, S.: Exploring potential of energy flexibility in buildings for energy system services, CSEE Journal of Power and Energy Systems 4 (4), 434–443 (2018).
14. Ghilardi, L.M.P.; Castelli, A.F.; Moretti, L.; Morini, M.; Martelli, E.: Co-optimization of multi-energy system operation, district heating/cooling network and thermal comfort management for buildings. Applied Energy 302, 117480 (2021).
15. Arteconi, A.; Mugnini, A.; Polonara, F.: Energy flexible buildings: A methodology for rating the flexibility performance of buildings with electric heating and cooling systems, Applied Energy 251, 113387 (2019).
16. Albadi, M.H.; El-Saadany, E.F.: A summary of demand response in electricity markets, Electric Power Systems Research 78, 1989–1996 (2008).
17. Heffner, G.; Goldman, C.; Kirby, B.; Kintner-Meyer, M.: Loads providing ancillary services: review of international experience. Ernest Orlando Lawrence Berkeley National Laboratory, LBNL–62701, ORNL/TM-2007/060, PNNL-16618, May 2007.
18. Amin, A.; Kem, O.; Gallegos, P.; Chervet, P.; Ksontini, F.; Mourshed, M.: Demand response in buildings: Unlocking energy flexibility through district-level electro-thermal simulation, Applied Energy 305, 117836 (2022).
19. Avramidis, I.A.; Capitanescu, F.; Evangelopoulos, V.A.; Georgilakis, P.S.; Deconinck, G.: In Pursuit of New Real-Time Ancillary Services Providers: Hidden Opportunities in Low Voltage Networks and Sustainable Buildings. IEEE Trans. Smart Grid 13 (1), 429–442 (2022).
20. Kazemi-Razi, S.M.; Askarian Abyaneh, H.; Nafisi, H.; Ali, Z.; Marzband, M.: Enhancement of flexibility in multi-energy microgrids considering voltage and congestion improvement: Robust thermal comfort against reserve calls, Sustainable Cities and Society 74, 103160 (2021).
21. Saavedra, A.; Negrete-Pincetic, M.; Rodríguez, R.; Salgado, M.; Lorca, Á.: Flexible load management using flexibility bands, Applied Energy 317, 119077 (2022).
22. Degefa, M.Z.; Bakken Sperstad, I.; Sæle, H.: Comprehensive classifications and characterizations of power system flexibility resources, Electric Power Systems Research 194, 107022 (2021).
23. Li, J.; Liu, F.; Li, Z.; Shao, C.; Liu, X.: Grid-side flexibility of power systems in integrating large-scale renewable generations: A critical review on concepts, formulations and solution approaches, Renewable and Sustainable Energy Reviews 93, 272–284 (2018).
24. Ma, O.; Alkadi, N.; Cappers, P.; Denholm, P.; Dudley, J.; Goli, S.; Hummon, M.; Kiliccote, S.; MacDonald, J.; Matson, N.; Olsen, D.; Rose, C.; Sohn, M.D.; Starke, M.; Kirby, B.; O'Malley, M.: Demand Response for Ancillary Services. IEEE Trans. Smart Grid 4 (4), 1988–1995 (2013).

25. D'Ettorre, F.; De Rosa, M.; Conti, P.; Testi, D.; Finn, D.: Mapping the energy flexibility potential of single buildings equipped with optimally-controlled heat pump, gas boilers and thermal storage. Sustainable Cities and Society 50, 101689 (2019).
26. Kim, Y.; Blum, D.H.; Xu, N.; Su, L.; Norford, L.K.: Technologies and magnitude of ancillary services provided by commercial buildings. Proceedings of the IEEE 104 (4), 758–779 (2016).
27. Ulbig, A.; Andersson, G.: Analyzing operational flexibility of electric power systems. Electrical Power & Energy Systems 72, 155–164 (2015).
28. Makarov, Y.; Loutan, C.; Ma, J.; de Mello, P.: Operational impacts of wind generation on California power systems. IEEE Trans. Power Syst. 24 (2), 1039–1050 (2009).
29. Chicco, G.; Riaz, S.; Mazza, A.; Mancarella, P.: Flexibility from distributed multienergy systems, Proceedings of the IEEE 108 (9), 1496–1517 (2020).
30. Good, N.; Mancarella, P.: Flexibility in multi-energy communities with electrical and thermal storage: a stochastic, robust approach for multi-service demand response. IEEE Trans. Smart Grid 10 (1), 503–513 (2019).
31. Hinker, J.; Knappe, H.; Myrzik, J.M.A.: Precise assessment of technically feasible power vector interactions for arbitrary controllable multi-energy systems. IEEE Trans. Smart Grid 10 (1), 1146–1155 (2019).
32. Neyestani, N.; Yazdani-Damavandi, M.; Shafie-khah, M.; Chicco, G.; Catalão, J.P.S.: Stochastic modeling of multienergy carriers dependencies in smart local networks with distributed energy resources. IEEE Trans. Smart Grid 6 (4), 1748–1762 (2015).
33. Vigna, I.; Pernetti, R.; Pasut, W.; Lollini, R.: New domain for promoting energy efficiency: energy flexible building cluster. Sustain. Cities Soc. 38, 526–533 (2018).
34. Tang, H.; Wang, S.: Energy flexibility quantification of grid-responsive buildings: Energy flexibility index and assessment of their effectiveness for applications. Energy 221, 119756 (2021).
35. Zhang, L.; Good, N.; Mancarella, P.: Building-to-grid flexibility: Modelling and assessment metrics for residential demand response from heat pump aggregations. Applied Energy 233–234, 709–723 (2019).
36. Arkhangelski, J.; Abdou-Tankari, M.; Lefebvre, G.: Ancillary services for distribution grid: demand response of building thermal inertia case. Proc. 2020 International Conference on Computational Intelligence for Smart Power System and Sustainable Energy (CISPSSE), Keonjhar, India, 2020.
37. Gao, Q.; Demoulin, M.; Wang, H.; Riaz, S. Mancarella, P.: Flexibility characterisation from thermal inertia of buildings at city level: a bottom-up approach. Proc. 2020 55th International Universities Power Engineering Conference (UPEC), 2020.
38. Good, N.; Karangelos, E.; Navarro-Espinosa, A.; Mancarella, P.: Optimization under uncertainty of thermal storage based flexible demand response with quantification of residential users' discomfort. IEEE Trans. Smart Grid 6 (5), 2333–2342 (2015).
39. Amadeh, A.; Lee, Z.E.; Zhang, K.M.: Quantifying demand flexibility of building energy systems under uncertainty, Energy 246, 123291 (2022).
40. Reynders, G.; Amaral Lopes, R.; Marszal-Pomianowska, A.; Aelenei, D.; Martins, J.; Saelens, D.: Energy flexible buildings: An evaluation of definitions and quantification methodologies applied to thermal storage, Energy & Buildings 166, 372–390 (2018).
41. Grønborg Junker, R.; Ghasem Azar, A.; Amaral Lopes, R.; Byskov Lindberg, K.; Reynders, G.; Relan, R.; Madsen, H.: Characterizing the energy flexibility of buildings and districts, Applied Energy 225, 175–182 (2018).
42. Vigna, I.; Lollini, R.; Pernetti, R.: Assessing the energy flexibility of building clusters under different forcing factors, Journal of Building Engineering 44, 102888 (2021).
43. Grønborg Junker, R.; Relan, R.; Madsen, H.: Designing individual penalty signals for improved energy flexibility utilisation. IFAC-PapersOnLine 52 (4), 123-128 (2019).
44. Klein, K.; Langner, R.; Kalz, D.; Herkel, S.; Henning, H.M.: Grid support coefficients for electricity-based heating and cooling and field data analysis of present-day installations in Germany. Applied Energy 162, 853–867 (2016).
45. Klein, K.; Herkel, S.; Henning, H.M; Felsmann, C.: Load shifting using the heating and cooling system of an office building: Quantitative potential evaluation for different flexibility and storage options. Applied Energy 203, 917–937 (2017).
46. Enescu, D.: A review of thermal comfort models and indicators for indoor environments. Renewable and Sustainable Energy Reviews 79, 1353–1379 (2017).
47. Stinner, S.; Huchtemann, K.; Müller, D.: Quantifying the operational flexibility of building energy systems with thermal energy storages, Applied Energy 181, 140–154 (2016).
48. Motegi, N.: Piette, M.A.; Watson, D.S.; Kiliccote, S.; Xu, P.: Introduction to commercial building control strategies and techniques for demand response. Lawrence Berkeley Nat. Lab., Tech. Rep. (LBNL-59975), May 2007.

49. Nguyen D.T.; Le, L.B.: Joint optimization of electric vehicle and home energy scheduling considering user comfort preference. IEEE Trans. Smart Grid 5 (1), 188–199 (2014).
50. Papadaskalopoulos, D.; Strbac, G.; Mancarella, P.; Aunedi, M.; Stanojevic, V.: Decentralized participation of flexible demand in electricity markets—Part II: Application with electric vehicles and heat pump systems. IEEE Trans. Power Syst. 28 (4), 3667–3674 (2013).
51. Lin, Y.; Mathieu, J.L.; Johnson, J.X.; Hiskens, I.A.; Backhaus, S.: Explaining inefficiencies in commercial buildings providing power system ancillary services. Energy & Buildings 152, 216–226 (2017).
52. Chen, Y.; Xu, P.; Gu, J.; Schmidt, F.; Li, W.: Measures to improve energy demand flexibility in buildings for demand response (DR): a review, Energy & Buildings 177, 125–139 (2018).
53. ASHRAE: Energy estimating and modeling methods. ASHRAE Handbook, Chapter 19. [Online] https://handbook.ashrae.org/Handbooks/F17/SI/f17_ch19/f17_ch19_si.aspx
54. Jin, X.; Wang, X.; Mu, Y.; Jia, H.; Xu, X.; Qi, Y.; Yu, X.; Qi, F.: Optimal scheduling approach for a combined cooling, heating and power building microgrid considering virtual storage system. Proc. 2016 IEEE Power and Energy Society General Meeting (PESGM), Tianjin, China, 17 July 2016.
55. Sikder, O.; Jansson, P.M.: Thermal inertia of a building as virtual energy storage: A sustainable solution for smart grids. Proc. 2018 53rd International Universities Power Engineering Conference (UPEC), Glasgow, Scotland, 4–6 September 2018.
56. Asare, P.; Ononuju, C.; Jansson, P.M.: Preliminary quantitative evaluation of residential virtual energy storage using power sensing. Proc. 2017 IEEE Sensors Applications Symposium (SAS), Glassboro, NJ, USA, 13–15 March 2017.
57. Fambri, G.; Badami, M.; Tsagkrasoulis, D.; Katsiki, V.; Giannakis, G.; Papanikolaou, A.: Demand flexibility enabled by virtual energy storage to improve renewable energy penetration. Energies 13, 5128 (2020).
58. Gusain, D.; Cvetković, M.; Palensky, P.: Quantification of operational flexibility from a portfolio of flexible energy resources, International Journal of Electrical Power & Energy Systems 141, 107466 (2022).
59. Mancarella, P.; Chicco, G.: Real-time demand response from energy shifting in distributed multi-generation. IEEE Trans. Smart Grid 4 (4), 1928–1938 (2013).
60. Mancarella, P.; Chicco, G.; Capuder, T.: Arbitrage opportunities for distributed multi-energy systems in providing power system ancillary services. Energy 161, 381–395 (2018).
61. Geidl, M.; Koeppel, G.; Favre-Perrod, P.; Klöckl, B.; Andersson, G.; Fröhlich, K.: Energy Hubs for the Future. IEEE Power and Energy Magazine 5 (1), 25–30 (2007).
62. Chicco, G.; Mancarella, P.: Matrix modelling of small-scale trigeneration systems and application to operational optimization. Energy 34 (3), 261–273 (2009).
63. Wang, Y.; Cheng, J.; Zhang, N.; Kang, C.: Automatic and linearized modeling of energy hub and its flexibility analysis. Applied Energy 211, 705–714 (2018).
64. Hao, H.; Sanandaji, B.M.; Poolla, K.; Vincent, T.L.: Aggregate flexibility of thermostatically controlled loads. IEEE Trans. Power Syst. 30 (1), 189–198 (2015).
65. Zhao, L.; Zhang, W.; Hao, H.; Kalsi, K.: A geometric approach to aggregate flexibility modeling of thermostatically controlled loads. IEEE Trans. Power Syst. 32 (6), 4721–4731 (2017).
66. Wang, G.; Li, Z.; Wang, F.: Enhanced sufficient battery model for aggregate flexibility of thermostatically controlled loads considering coupling constraints. IEEE Trans. on Sustainable Energy 12 (4), 2493–2496 (2021).
67. Wu, D.; Wang, P.; Ma, X.; Kalsi, K.: Scheduling and control of flexible building loads for grid services based on a virtual battery model, IFAC-PapersOnLine, 53 (2), 13333–13338 (2020).
68. Hughes, J.T.; Domínguez-García, A.D., Poolla, K.: Identification of virtual battery models for flexible loads. IEEE Trans. Power Syst. 31 (6), 4660–4669 (2016).
69. Hao, H.; Wu, D.; Lian, J.; Yang, T.: Optimal coordination of building loads and energy storage for power grid and end user services. IEEE Trans. Smart Grid 9 (5), 4335–4345 (2018).
70. Heussen, K.; Koch, S.; Ulbig, A.; Andersson, G.: Unified system-level modeling of intermittent renewable energy sources and energy storage for power system operation. IEEE Systems Journal 6 (1), 140–151 (2012).