New domain for promoting energy efficiency: Energy Flexible Building Cluster

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Abstract: The ongoing energy system shift—from traditional centralized fossil fuel based to decentralized renewable energy sources based—requires a strengthened control of energy matching. Smart buildings represent the latest step in building energy evolution and perform as active participants in the cluster/energy infrastructure scale, becoming energy prosumers. In this framework, the IEA EBC Annex 67 introduces the concept of 'Energy Flexible Building', defined as a building able to manage its demand and generation in accordance with local climate conditions, user needs and grid requirements. Currently, there is no insight into how much flexibility a building may offer, and this study aims to overview the theoretical approaches and existing indicators to evaluate the Energy Flexibility of building clusters. The focus on cluster scale allows for the exploitation of the variation in energy consumption patterns between different types of buildings and the coordination of load shifting for the improvement of renewable energy use. The reviewed indicators can contribute to the definition of the Smart Readiness Indicator, introduced in the European Commission proposal for the EPBD revision, in order to test a building's technological readiness to adapt to the needs of the occupants and the energy environment, as well as to operate more efficiently.

Highlights:

- First steps towards the definition of Energy Flexibility at cluster scale
- Overview of indicators for quantifying Energy Flexibility at cluster scale
- Support in the definition process of Smart Readiness Indicator

Keywords: Energy Flexibility, Building cluster, Energy efficiency, Indicators, Smart Readiness Indicator

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1. Introduction

The "Clean Energy for All European" package (EC, 2016a) of the European commission sets out the energy policy framework going toward 2030, and treats buildings as an essential part of Europe's clean energy transition. The principle "energy efficiency first" (EC, 2015) drives the transformation of the conventional centralized energy system based on fossil fuels into an efficient decentralized system powered by renewable energy sources.

Energy systems based on Variable Renewable Energy sources are characterized by intermittent generation, and their rapid increase challenges the stability of both thermal and electric grids (Whiteman, Rinke, Esparrago, & Elsayed, 2016). A mitigating effect of the stress put on the grid by variable renewable energy sources (VRES) penetration can be played by buildings, which are gradually moving from stand-alone consumers to interconnected prosumers (both producers and consumers) able to provide and store renewable energy and actively participate in demand response.

Despite the fact that the Energy Performance of Buildings Directive (EU, 2010) and the Renewable Energy Directive (EU, 2009) have stimulated the deployment of on-site renewable energy systems, the on-site (or nearby) renewable energy production and self-consumption in European countries are not at their full potential. This is partly due to rigid regulatory frameworks and lack of investments. The instantaneous sharing of produced energy among buildings is allowed or encouraged only in a few Member States and currently the storage technologies are too expensive for massive application. Therefore, it is necessary to identify solutions aimed at changing the relationship between the grid and the consumers. Future buildings should adapt their energy demand to the needs of the grid and the renewable production, while maintaining high comfort standards and low operating costs.

In recent years, we have observed a deep evolution of the building design approach in terms of targets, technology functions, overall performances and domain (Fig. 1). The evolutionary path of building transformation started with *passive buildings* intended to minimize the energy demand through passive solutions (building envelope domain), then evolved into the *nearly Zero Energy Buildings* (nZEB) aimed at obtaining an energy balance (consumption-production) through on-site generation from RES (building as energy system domain) (Paoletti, Pascual Pascuas, Pernetti, & Lollini, 2017), and will now find its latest evolution in the energy matching required by *smart buildings* in order to improve resilient building behavior coupled with grid interaction (cluster/energy infrastructure domain).

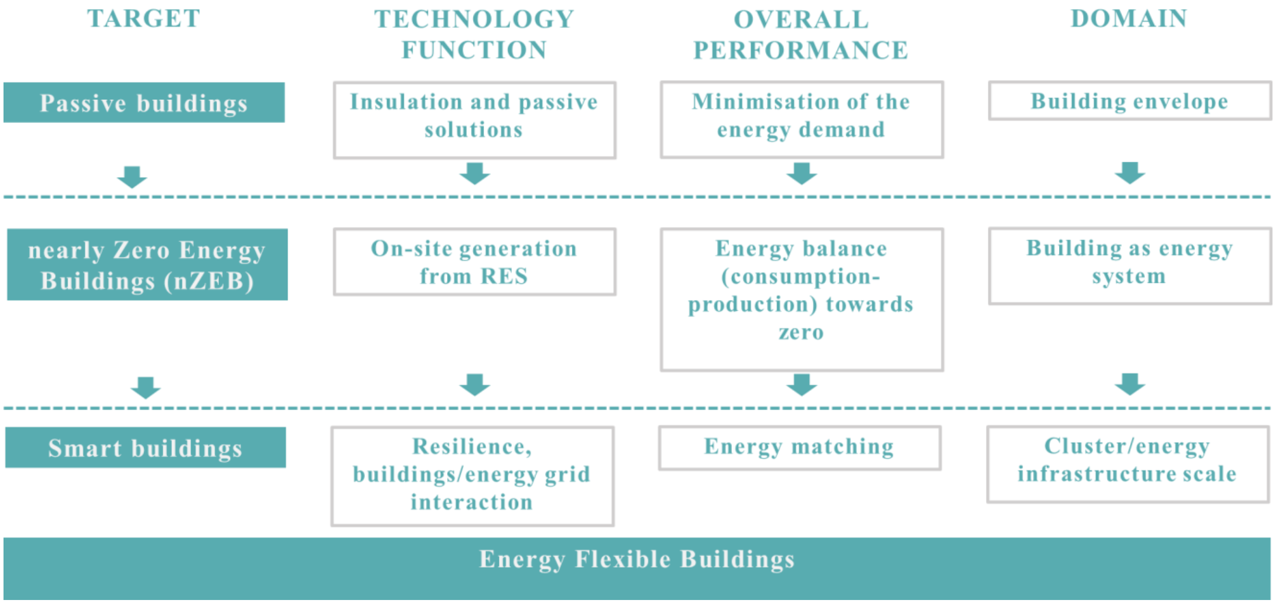

Fig. 1 *Evolutionary path of building transformation*

Within this framework, the International Energy Agency (IEA), in the programme ‘Energy in Buildings and Communities’ (EBC), introduces the concept of ‘Energy Flexible Buildings’ with the project ‘Annex 67’ (IEA EBC ANNEX 67). Based on the initial definition of Annex 67, building Energy Flexibility represents “the capacity of a building to manage its demand and generation according to local climate conditions, user needs and grid requirements. Energy Flexibility of buildings will thus allow for demand side management/load control and thereby demand response based on the requirements of the surrounding grids”.

From a different perspective, Energy Flexibility could also be defined as the capacity of a building to react to one or more forcing factors, in order to minimize CO_2 emissions and maximize the use of Renewable Energy Sources (RES). The forcing factors represent a set of significant boundary conditions that could change during the lifetime of a building and have different levels of frequency:

- *Low frequency factors* (temporal fluctuations within the years-decades time range): climate change, macro-economic factors, technological improvement, building intended use and variation in the number of occupants, demographic changes (e.g. age, income);
- *High frequency factors* (temporal fluctuations within the minutes-hours time range): internal loads, solar loads, user behavior, energy prices.

Starting from the initial definition, the work planned within Annex 67 deals with three main topics: metrics and indicators able to represent Energy Flexibility in buildings, simulation and evaluation of technology solutions (passive, active, and control strategies) and the potential influence of user behaviour on an Energy Flexible Building. One of the issues faced within this Annex is the Energy Flexibility assessment at cluster level. It is meant to be an intermediate level between a single building and districts or the whole city, and it offers the possibility to achieve performance enhancement and cost optimization through a mutual collaboration between generation, storage, and consumption units (AIA National, 2007; Crosbie, Short, Dawood, & Charlesworth, 2017; Shen & Sun, 2016).

The present paper aims to make a comprehensive overview of the theoretical approaches, currently described in the literature, for the evaluation of Energy Flexibility of building clusters in order to provide the framework for the performance assessment of the future generation of Energy Flexible buildings. In particular, the section *Energy Flexibility in the European perspective* reports the current EU Commission development of a “Smart Readiness Indicator”; the chapter *Energy Flexible Building Clusters* clarifies the importance of designing at cluster scale, then explains the meaning of the word ‘cluster’ (definition) and the level of interaction among buildings (connection) and finally reports some key concepts adopted so far in the literature to describe the synergy of energy efficient buildings and renewable energy utilization at an aggregated level; the last section, *Reviewed indicators for evaluating Energy Flexibility at the building cluster level*, focuses on existing metrics and indicators that can be used to quantify Energy Flexibility at cluster scale.

2. Energy Flexibility in the European perspective

In addition to being the focus of Annex 67, Energy Flexibility represents a key issue to be addressed also according to the European Commission. Considering the transition toward clean energy, the interaction between buildings and the spread of information to consumers regarding operational energy consumption can contribute to RES maximization at a local level. In this regard, the “Clean Energy for All Europeans” package, the proposal for amending EPBD (EC, 2016b), introduces a ‘Smart Readiness Indicator’ (SRI). The “Common general framework methodology for the calculation of 'Smartness Indicator' for Buildings” of the proposal for amending EPBD focuses on key SRI functionalities: (*i*) the technological readiness assessment of a building’s capacity to adapt to user needs and energy environment; (*ii*) the evaluation of building readiness in operating more efficiently and (*iii*) the measurement of the readiness of building interaction in demand response with the energy system and the district infrastructure.

The introduction of such a SRI will increase building users’ consciousness of the fundamental role of smart technologies and ICT solutions, encouraging the spread of healthier and more comfortable buildings with lower energy use and carbon impact, while facilitating RES integration.

The current state of discussion at the EU level evaluates the flexibility according to the number and features of the building components with a qualitative approach, whereas the characterization and methodology defined within the Annex 67 will provide a quantitative evaluation of the flexibility associated with a building, by using measured physical data and results from simulation campaigns. Therefore, the approach being defined within the Annex 67 can be coupled and applied within the framework of the evaluation of Smart Readiness Indicator, providing a quantitative evaluation of the flexibility associated with a building.

In order to properly create the SRI indicator, it is necessary to identify smart services, i.e. services that use smart technologies to facilitate energy management and interact with building occupants’ behaviors to fulfil their comfort needs (Verbeke, Ma, Bogaert, Tichelen, & Uslar, 2017). The concept of ‘functionality levels’ can be introduced to value the smartness of service implementation, ranging from basic functionality to fully integrated smart solutions (Fig. 2).

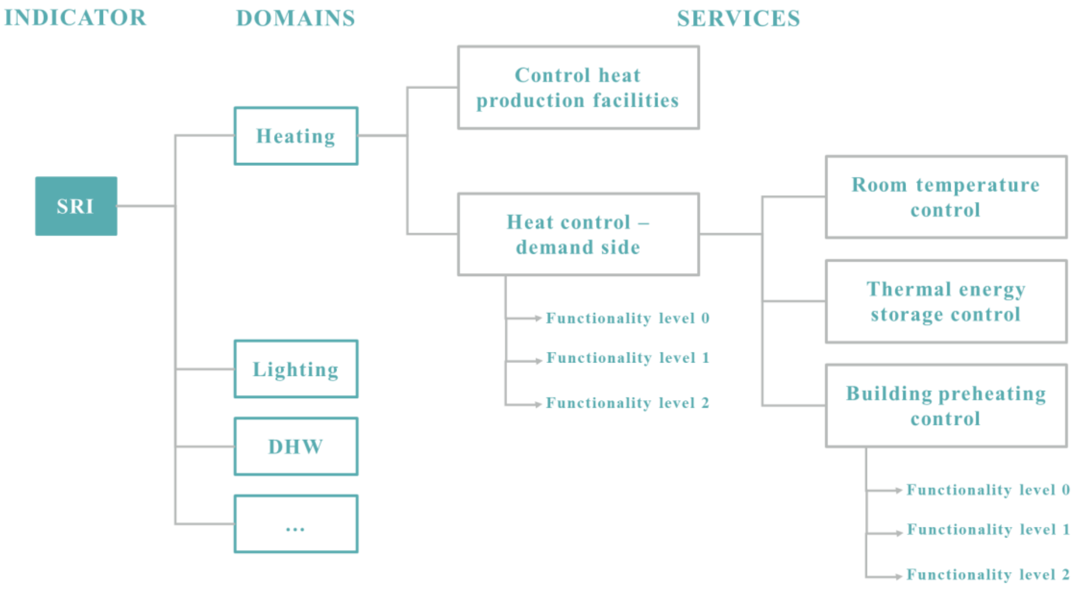

Fig. 2 *Excerpt from structure of the service list* (Verbeke et al., 2017)

The review and investigation of Energy Flexible indicators can contribute to defining the proper smart technologies that are able to store thermal and electrical loads, to improve load shifting potential of buildings while maintaining required comfort levels, and support the physical quantification of functionality levels.

3. Energy Flexible Building Clusters

3.1 Why cluster scale?

In an evolving energy system, shifting from single energy efficient units to interconnected active players that manage the energy flows, the relationship between the buildings and the grid significantly changes. Smart buildings are able to both consume and produce energy and they increasingly interact with the energy infrastructure by acting as micro energy hubs (D'Angiolella, De Groote, & Fabbri, 2016).

Energy planning at the building cluster scale represents an effective strategy for providing local and low-carbon energy supply, through the enhancement of district energy systems and decentralized energy production. In the European context, the combination of energy efficiency improvement with renewable energy integration at the cluster scale has been investigated in a considerable number of strategically selected case studies (e.g. the BedZED eco-community in London, Vauban in Freiburg, Hammarby in Stockholm (Williams, 2016)). The results reveal that the management of a shared distribution network powered by solar thermal or combined heat and power (CHP) plants can bring several benefits to individual buildings in terms of increased efficiency, higher possibilities of storage and load complementarity due to building usage differences (e.g. commercial and residential) (IPCC, 2007).

Furthermore, the focus on cluster scale enables the development of a systemic approach in building design that considers, in an economy of scale perspective, factors such as retrofitting and adoption of technologies/strategies for increasing energy efficiency and minimizing CO_2 emissions, so as to reduce the unitary cost of investment and reach cost-optimality (Koch & Girard, 2013).

Therefore, the opportunity to enlarge the design at the cluster scale can yield progress toward the aim to reduce carbon emissions.

3.2 Definition of building clusters

The investigation of the ‘building cluster’ concept is the starting point necessary for defining common rules and specific characteristics -e.g. size, composition, owner, type of connection with other buildings. Indeed, in the literature it is possible to find several terms and definitions related to the cluster concepts according to different perspectives, but there is not a univocal description of clusters’ features.

Urban social scientists introduce the concept of *neighborhood*, focusing on its spatial attributes - geography, infrastructure and buildings - and on the social collective relations that characterize the space. (Galster, 2001).

The term *community* could identify, on the one hand, a group of buildings located in the same area and, on the other hand, a “portfolio of buildings” geographically far but owned by a single person or set of occupants (Managan & Controls, 2012).

Moreover, the definition of cluster can be linked to the concept of *Net Zero Energy Communities* (NZECs), characterized by a null or positive value in the difference between annual delivered energy and on-site renewable exported energy (He, Huang, Zuo, & Kaiser, 2016). The community can be considered the crucial scale for reaching the target of net zero energy, for improving energy interdependency and reducing maintenance and life-cycle costs. In fact, compared to a single building, the community level ensures a larger accommodation of RES supply systems and an easier flattening of load profiles due to highly varying occupancy patterns.

Thus, the building cluster concept will fundamentally transform the energy system by shifting on-site energy generation from a single Net Zero building to a system of "*Net Zero clusters*", able to freely share distributed power generation and storage devices, in order to achieve maximum energy efficiency (Li, Wen, & Wu, 2014).

Starting from the previous reviews, a new definition of cluster is suggested and adopted in the present paper as follows: a building cluster identifies a group of buildings interconnected to the same energy infrastructure, such that the change of behaviour/energy performance of each building affects both the energy infrastructure and the other buildings of the whole cluster. This definition does not assign fixed dimension and boundaries to the building cluster scale, but it is based on building interconnection that could be physical and/or market related.

The *physical connection* to the same grid of building clusters allows the exchange of energy between buildings (e.g. PV panels installed in one building produce energy that can be used also by the other buildings) or from a central source toward the buildings (e.g. district heating).

The possible presence of *market aggregation* (Eurelectric, 2014) enables the management of the building cluster by a common agent or company who can potentially exploit the Energy Flexibility of the whole cluster (Langham, Cooper, & Ison, 2013; SF Environment, 2013). In general, different buildings can be treated as elements of the same cluster although they are not located in the same area (multi-site aggregation), e.g. different buildings with the same owner that can negotiate better energy tariffs with the DSO, offering in exchange a reduction of the energy consumption when required by the grid.

3.3 First steps towards the Energy Flexibility concept at the building cluster scale

One of the specific objectives of Annex 67 is the development of a common definition of 'Energy Flexible Building Cluster', in order to create a common basis for the work and to explain what Energy Flexibility is and how it can be evaluated.

As a general definition, starting from the approach set out for single buildings and reported in the introduction, Energy Flexible Building Clusters should demonstrate the capacity to react to forcing factors in order to minimize CO_2 emissions and maximize the use of Renewable Energy Sources (RES).

Nevertheless, the absence of a consolidated definition requires as a starting point the analysis of some auxiliary concepts adopted so far in the literature used to describe the synergy of energy efficient buildings and renewable energy utilization at an aggregated level; all of these concepts contain important keywords that will be included in the final definition elaborated during the Annex 67 work.

The auxiliary concepts identified are the following: (*i*) *Smart Building Cluster* and (*ii*) *Zero Energy Neighbourhood* concepts stressing the role of smart interaction between buildings and grid and underlining the importance of reasoning at an aggregated level to reach the aim of Zero Energy Buildings; (*iii*) *Micro Energy Hub* concept, representing the future behaviour of buildings, that will be able to consume, produce and store energy and will increasingly interact to reduce peak demand and grid stress; (*iv*) *Virtual Power Plant* concept as a strategy for aggregating heterogeneous Distributed Energy Resources (DERs) to relieve the load on the grid by smartly distributing the power generated by the individual units during periods of peak load; (*v*) *Collaborative Consumption* concept as a social agreement by users to share their energy sources; (*vi*) *Local Energy Community* concept introduced by the European Commission in the "Winter Package" as new market players with the right to generate, consume, store and sell renewable energy.

It is important to refer to such auxiliary concepts, further detailed in the following sections, since they represent an expression of the market stakeholders and players involved in the ongoing energy transition towards the ambitious 100% RES target. Policy makers should start from these auxiliary concepts in order to effectively promote energy efficiency in the current crucial transformation of market, building and infrastructure technologies, as well as EU legislative framework.

I. Smart Building Cluster

The concept of Energy Flexibility at an aggregated level can be linked to the definition of "*Smart Building Cluster* (SBC)", indicating "a group of neighboring smart buildings electrically interconnected to the same micro-grid" (Ma et al., 2016). Considering the SBC scale, it is possible to obtain an improvement of the local use of renewable energy, a decrease in the cost of electricity consumption, and a larger load shift in time due to different occupancy patterns and varying load profiles within a cluster composed of mixed-use buildings.

II. Zero Energy Neighborhood

The "Zero Energy Building" concept still considers the individual buildings as autonomous entities and neglects the importance of reaching energy efficiency at a larger scale. In the future shift to NZEB 2.0 (D'Angiolella et al., 2016) the *Zero Energy Neighborhood* scale will take into account the numerous interactions between urban form, building energy needs and on-site production of RES (A.-F. Marique & Reiter, 2014), in order to balance annual building energy consumption and individual transportation by the local production of renewable energy (A. Marique, Penders, & Reiter, 2013).

III. Micro Energy Hub

In the framework of an Energy Flexible Building Cluster, buildings will increasingly interact with the energy systems and have the potential to take up an important role in the energy-supply-system stability by acting as *micro energy hubs* i.e. “multi hubs-generation systems, providing renewable energy production, storage and demand response” (Geidl, Koeppel, Klockl, Andersson, & Frohlich, 2007).

The key concept of the energy hub approach is the possibility to jointly manage the energy flows from multiple energy sources in order to improve the renewable energy sharing between different interconnected buildings (Darivianakis, Georghiou, Smith, & Lygeros, 2015; Orehounig, Mavromatidis, Evins, Dorer, & Carmeliet, 2014).

IV. Virtual Power Plant

It is possible to make an analogy between Energy Flexible Building Clusters and virtual power plants: in fact, Virtual Power Plants (VPP) are “collective generators of renewable energy sources that can store and adjust energy output on demand and at will” (Carr, 2011). An aggregator can group different distributed energy resource (DER) systems into a VPP in order to provide more Energy Flexibility than a single system and, in parallel, Energy Flexible buildings have the possibility to co-generate with current grids or operate solely to produce energy in a cost-effective way, while adapting/shifting the electricity consumption profile in time (De Coninck & Helsen, 2013).

V. Collaborative Consumption

In the current market, end-users hold only the role of final consumers and are not involved in the energy supply side. The community engagement to reach a suitable energy management framework represents an opportunity to increase social acceptance of distributed generation in smart grids (Ahmadi, Rosenberg, Lee, & Kulvanitchaiyanunt, 2015). Collaborative consumption (CC) is “a social-based agreement framework”, in which different consumers cooperate to share their resources and to create valuable services for the benefit of the whole community (Belk, 2010). Therefore, an active participation of residents into the energy market improves their inclination towards cooperation in order to reschedule their consumptions and generate more renewable energy so as to minimize energy cost, carbon emissions and primary energy consumption (Dai, Hu, Yang, & Chen, 2015).

VI. Local Energy Community

The European Commission proposal for a recast of the International Electricity Market Directive (EC, 2016c) establishes a framework for Local Energy Communities aimed at improving energy management at the community level and empowering local participants. In such a geographically confined network, all consumers can have a direct involvement in energy consumption, storage and/or the sale of self-generated electricity to the market, and the up-take of new technologies and consumption patterns, including smart distribution grids and demand response, will get easier.

4. Reviewed indicators for evaluating Energy Flexibility at the building cluster level

Indicators are fundamental for quantifying the amount of Energy Flexibility that a building can offer, and measure how different aspects influence the sharing of renewable energies and the reduction of peaks of delivered energy demand in buildings. Indicators are also a way to effectively communicate the energy flexibility concept, providing a common language between energy players and supporting policy makers in the quantification of the actual impact of novel energy related policies.

A first literature review showed that the majority of existing indicators and approaches, related to Energy Flexibility quantification, just focuses on single buildings. This research study identifies a set of potential key performance indicators that could be adapted to the cluster scale and used to characterize Energy Flexible Building Clusters. The selected indicators have been classified into five different categories, as reported in Table 1:

1. The *Cost level* focuses on Energy Flexibility quantification with respect to costs.
2. The *Thermal level* includes indicators:

   - of Energy Flexibility related to the possibility to activate the envelope/structural mass of the building;
   - referred to the Energy Flexibility that could be provided by controllable loads such as the consumed power of HVAC systems;
   - related to the thermal grid;
   - of thermal comfort related to the acceptance of indoor conditions by occupants (temperature fluctuations, air quality, etc.).

3. The *Electric level* comprises indicators referred to the measure of electric grid control over the demand and to the relation between on-site generation and load for a specific temporal resolution.

4. The *Thermal-electric level* encloses indicators related to cumulative energy demand/supply.
5. The *Other relevant indicators* section includes indicators related to other auxiliary issues that influence the energy flexibility, such as the influence of the typological composition of a cluster on energy consumption and the readiness of a building to adapt its operation to the needs of the occupants and of the grid to improve its performance.

Table 1 *Reviewed indicators for Energy Flexible Building Cluster*

Energy Flexible Building Cluster Indicators
Costs
Specific Cost of Flexibility Spark Spread Total Supply Spread Flexibility Factor
Thermal level
Available Storage Capacity Comfort Index
Electric level
Grid Control Level Load Matching Index Grid Interaction Index
Thermal-Electric level
On-site Energy Ratio Annual Mismatch Ratio Maximum Hourly Surplus Maximum Hourly Deficit Ratio of Peak Hourly Demand to Lowest Hourly Demand
Other relevant indicators
Homogeneity Index Smart-ready Built Environment Indicator

I. Energy Flexibility Indicators related to costs

In the study of De Coninck & Helsen, 2013, Energy Flexibility is intended as “the possibility to deviate the electricity consumption profile compared to a reference business as usual (BAU) scenario”. In order to quantify the potential flexibility at the cluster scale, multiple cost curves, as can be seen from *Figure 3*, can be aggregated and for every point on the cost curve it is possible to obtain the ***Specific Cost of Flexibility*** c_{sp} expressed as the ratio between the extra cost for flexibility ΔC [c€] and the range of variability of the electricity consumption ΔE [kWh] due to flexibility (in comparison to the BAU scenario) (*Equation 1*):

$$c_{sp} = \frac{\Delta C}{|\Delta E|}$$

Equation 1

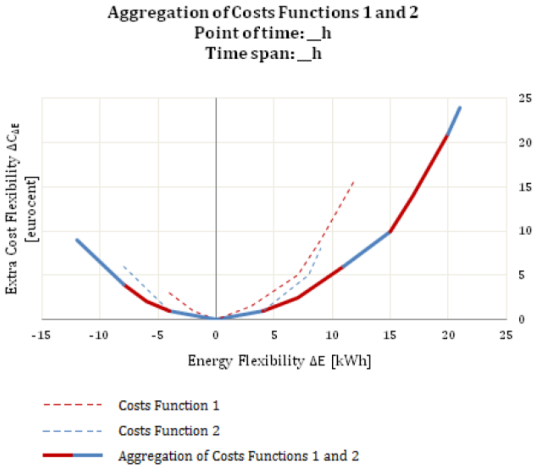

Fig. 3 *Aggregation of two cost functions showing the flexibility of electricity consumption on the horizontal axis and the corresponding additional cost compared to the business as usual on the vertical axis*

The study of Piacentino et al. (Piacentino & Barbaro, 2013) introduces two further indicators that can be applied at the cluster scale, the *Spark Spread* and the *Total Supply Spread*, to express the convenience of self-producing heat and electricity compared to energy purchased from the public grid. The ***Spark Spread*** (SS) is defined as the “ratio between the *market price* MP_e of electricity (expressed in €/kWh) and the cost of the amount of fuel consumed by the ‘combined heat and power’ (CHP) unit to produce 1 kWh electricity” (*Equation 2*):

$$SS = \frac{MP_e}{\frac{1}{\eta_e^{CHP}} \cdot \frac{3600}{LHV_{fuel}^{CHP}} \cdot MP_{fuel}^{CHP}}$$

Equation 2

with *low heat value of fuel* LHV^{CHP}_{fuel} expressed in kJ/Nm^3 or kJ/kg, respectively for gaseous and liquid fuels, and *market price* MP^{CHP}_{fuel} expressed in €/Nm^3 or €/kg.

Compared to the previous one, the second indicator, named ***Total Supply Spread*** (*Equation 3*), adds at numerator the cost that should be sustained to supply by a traditional boiler the amount of heat $1/PHR^{CHP}$ (where PHR^{CHP} is the *power to heat ratio* of the prime mover) actually recoverable when 1 kWh of electricity is produced in cogeneration mode.

$$\mathrm{TSS} = \frac{MP_e + \frac{1}{PHR^{CHP}}\cdot\frac{1}{\eta_{boil}}\cdot\frac{3600}{LHV_{fuel}^{boil}}\cdot MP_{fuel}^{boil}}{\frac{1}{\eta_e^{CHP}}\cdot\frac{3600}{LHV_{fuel}^{CHP}}\cdot MP_{fuel}^{CHP}}$$

Equation 3

Le Dréau & Heiselberg, 2016 calculate a ***Flexibility Factor***, that can prove the “ability to shift the energy use from high to low price periods”, as reported in *Equation 4* referred to heating energy consumption. Low price period is referred to a price which is lower than the first quartile (evaluated over two weeks); a high price corresponds to a price which is higher than the third quartile. In this equation a null value indicates that the heating use is similar in low and high price periods, a positive unitary value expresses that heating energy use is not used in high price periods and finally a negative unitary value means that no heating energy is used in low price periods.

$$Flexibility\ Factor = \frac{\int_{low\ price\ time} q_{heating}dt - \int_{high\ price\ time} q_{heating}dt}{\int_{low\ price\ time} q_{heating}dt + \int_{high\ price\ time} q_{heating}dt}$$

Equation 4

Similar equations could be defined also for further energy use. This indicator is quite intuitive and easy to be calculated, nevertheless it does not give any information on how much load can be shifted thanks to energy flexibility and it does not provide any suggestions on how to improve the operation. Furthermore, the definition of the low and high price periods strongly affects the results of the index, and a more univocal approach should overcome the problem.

II. Energy Flexibility Indicators related to thermal level

Reynders, 2015 defines the ***Available Structural Storage Capacity for Active Demand Response*** C_{ADR} (*Equation 5*) as “the amount of heat that can be absorbed by the structural mass of a building without jeopardizing indoor thermal comfort in a specific time-frame and given the dynamic boundary conditions”. The Available Structural Storage Capacity, expressed in kWh, can be quantified as:

$$C_{ADR}\left(t, l_{ADR}, U(t), dT_{comf}(t), \theta\right) = \int_0^{l_{ADR}} (\dot{Q}_{ADR} - \dot{Q}_{Ref})dt$$

Equation 5

with l_{ADR} indicates the duration of the Active Demand Response (ADR) event, $U(t)$ the dynamic boundary conditions such as climate and occupant behaviour, $dTcomf\ (t)$ the comfort range available for ADR which may vary in time, Q_{ADR} the heat demand for active demand response and Q_{ref} the reference heat demand. This indicator can explain how the design and the properties of the buildings within a cluster may affect their energy performance and suitability for active demand response without compromising comfort.

Another indicator dealing with the indoor conditions of a NZEB Cluster is the ***Comfort Index*** (Shen & Sun, 2016), expressing the thermal discomfort resulting from the cooling supply time failure of a sized air-conditioning system. The Comfort Index is expressed in *Equation 6*:

$$PE_{comfort} = \sum \tau_i \begin{cases} \tau_i = 1, & if\, CAP_{AC} < CL_i \\ \tau_i = 0, & if\, CAP_{AC} \geq CL_i \end{cases}$$

Equation 6

where $PE_{comfort}$ is the comfort index, τ_i represents failure time value of *i*th hour, CAP_{AC} is the air-conditioning system size, CL_i is the cooling load profile.

III. Energy Flexibility Indicators related to electric level

The study of Ahmadi et al., 2015 proposes a method for categorizing residential loads according to consumer needs:

1) “first priority loads” are non-reschedulable usage and service loads, which provide fundamental and uninterruptible services for users;
2) “second priority loads” are reschedulable usage loads of appliances that use thermal storage and which use is deferrable to near future periods still providing acceptable comfort;
3) “third priority loads” are referred to the reschedulable/deferrable loads, resulting from e.g., dishwashers, washing machines and dryers’ usage.

Grid Control Level, denoted by φ, represents “a measure of a microgrid’s control over the demand”. It is calculated as the sum of controllable second and third priority loads divided by the total load as reported in *Equation 7*:

$$\varphi = \frac{\theta_2+\theta_3}{\theta_1+\theta_2+\theta_3}$$

Equation 7

θ_1, θ_2, and θ_3 represent the total amount of first, second and third priority loads in kW, respectively. A 0 value expresses the absence of control by the central controller and the necessity to use most of its generation for demand supply, while the value 1 indicates the capacity of the central controller to flexibly delay the demand of the cluster and partly sell electricity to the grid if the market price is attractive.

Load Matching Index, proposed by Voss et al., 2010, is expressed as the relation of the on-site generation to the load for a specific temporal resolution. This indicator is useful to assess the on-site energy use and it helps to differentiate between the different timescales and although this concept was specifically developed for single buildings, the same idea can be applied to building clusters connected to the same local grid. The Load Matching Index $f_{load,i}$, expressed in percentage [%] and influenced by the time interval i [h,d,m], can be formulated in function of load metering (*Equation 8*) or net metering (*Equation 9*), while the presence of an on-site battery modifies the index (*Equation 10*) by adding the battery energy balance to the on-site generation. The Load Matching Index indicates the amount of energy that can be generated by RES and stored with batteries in comparison to the load; in addition, as indicated in *Equation 9*, it gives indications to the amount of exported energy in comparison to the on-site generation.

$$f_{load,i} = min\left[1, \frac{on\ site\ generation}{load}\right] \cdot 100$$

Equation 8

$$f_{load,i} = min\left[1, \frac{on\ site\ generation}{net\ metering + on\ site\ generation}\right] \cdot 100$$

Equation 9

$$f_{load,i} = min\left[1, \frac{on\ site\ generation + battery\ balance}{load}\right] \cdot 100$$

Equation 10

The ***Grid Interaction Index*** (Voss et al., 2010) describes the average grid stress, using the standard deviation of the grid interaction over a period of a year. The Grid Interaction Index $f_{grid,i}$, expressed in percentage [%] and in relation to the time interval i [h,d,m], can be useful to express the variation of the energy exchange between a building cluster and the grid and it is defined as “the ratio between net grid metering over a given period compared to the maximum/minimum value within an annual cycle” (*Equation 11*).

$$f_{grid,i} = \frac{net\ grid}{max|net\ grid|} \cdot 100$$

Equation 11

IV. Energy Flexibility Indicators related to thermal-electric level

The ***On-site Energy Ratio*** (OER) (Ala-juusela & Sepponen, 2014) is defined as “the ratio between annual energy supply from local renewable sources and annual energy demand” (*Equation 12*):

$$OER = \frac{\int_{t_1}^{t_2} G(t)dt}{\int_{t_1}^{t_2} L(t)dt}$$

Equation 12

where G(t) is the on-site energy generation power and L(t) is the load power of all energy types (heating, cooling, electricity) combined. The indicator is calculated by aggregating energy production and consumption of different types of buildings at the cluster scale. Considering net annual balance, a unitary value indicates that the energy demand is completely covered by RES supply, while a value higher than 1 describes an energy positive neighborhood, in which the annual energy demand is lower than the annual energy supply from local renewable energy sources. This indicator by itself does not measure the Energy Flexibility of a cluster, but it should be coupled with the following three indicators: Annual Mismatch Ratio, Maximum Hourly Surplus and Maximum Hourly Deficit.

The ***Annual Mismatch Ratio*** (Ala-juusela & Sepponen, 2014) expresses the annual difference between demand and local renewable energy supply in a cluster of buildings and, for each energy type, AMR_x (x = h for heat, c for cool, e for electricity) is calculated by taking an average of the Hourly Mismatch Ratios HMR_x (*Equation 13*):

$$AMR_x = \frac{\sum_{t=1}^{8760} HMR_x(t)}{8760}$$

Equation 13

For each energy type, the ***Maximum Hourly Surplus*** (MHS_x) (Ala-juusela & Sepponen, 2014) indicates “the maximum hourly ratio of difference between on-site generation and load over the load for each energy type”. It is calculated as reported in *Equation 14*:

$$MHS_x = Max\left[\frac{\int_{t_1}^{t_2}[G_x(t) - L_x(t) - S_x(t)]dt}{\int_{t_1}^{t_2} L_x(t)dt}\right]$$

Equation 14

where $G_x(t)$ is the on-site energy generation rate of the energy type, $L_x(t)$ is the load for that type and $S_x(t)$ is the rate of storage loading or discharge. A building cluster that is supplying more than its demand will be characterized by high values of OER and MHS, while when the RES supply of the cluster is not optimally planned, we obtain low OER and high MHS values.

The role of local storage in the ratio between load and RES on-site generation in a cluster can be taken into account by calculating the ***Maximum Hourly Deficit*** (MHDx) for each energy type (Ala-juusela & Sepponen, 2014). In *Equation 15*, $S_x(t)$ represents the storage discharge rate (negative value).

$$MHD_x = Max\left[\frac{\int_{t_1}^{t_2}[L_x(t) - G_x(t) + S_x(t)]dt}{\int_{t_1}^{t_2} L_x(t)dt}\right]$$

Equation 15

A proper way to characterize the magnitude of the peak power demand of a cluster is the calculation of the ratio between the highest and lowest peak values for hourly demand over the month, expressed for each energy type by the ***Ratio of Peak Hourly Demand to Lowest Hourly Demand*** (Ala-juusela & Sepponen, 2014).

V. Other relevant Energy Flexibility Indicators

Considering the cluster composition, Jafari-marandi et al., 2016 propose an index to determine which type of buildings should form a cluster and what is the impact of building clusters' heterogeneity based on energy profile on the energy performance of building clusters. The ***Homogeneity Index*** HI_j expresses the average correlation of buildings' energy profiles within the same cluster. Small values of this indicator indicate a more cost-effective usage of shared energy and correspond to highly heterogeneous building clusters' composition. The indicator is calculated according to *Equation 16:*

$$HI_i = \frac{\sum_{j=1}^{N_{C_i}} \sum_{k=j+1}^{N_{C_i}} Cor\left(M_J^{C_i}, M_k^{C_i}\right)}{N_{C_i} \times (N_{C_i} - 1)/2}$$

Equation 16

where ${}_i$ is the index for different clusters, Nc_i is the number of buildings in the cluster i, M_j^{Ci} is the jth member of the cluster i, and $Cor(x, y)$ is the correlation between x and y.

The ***Smart Built Environment Indicator*** (SBEI) developed by the Buildings Performance Institute Europe (BPIE) supports the assessment of EU countries' readiness to transition to smart buildings. The key aspects considered by the SBEI to describe how smart-ready the built environment is are related to the energy performance of the building stock, the share of energy from renewable sources, the smart meter deployment, the development of a dynamic energy market, the improvement of the access to demand response, the roll-out of building energy storage and the market penetration of electric vehicles (De Groote, Volt, & Bean, 2017). The specific application of this indicator is intended for entire countries, but the characteristics considered are scalable also to a small cluster context and useful to evaluate the flexibility also at an aggregated level.

5. Conclusions

The foreseen large deployment of renewable energy sources may seriously affect the stability of energy grids and it will be necessary to control energy consumption or evaluate the feasibility of installing batteries and storage systems (both active and passive) in order to match instantaneous energy production. Energy Flexibility in buildings will allow for demand side management and load control and thereby demand response according to climate conditions, user needs and grid requirements. In the framework of the research IEA EBC Annex 67, a literature review was conducted to define building clusters and describe existing indicators to quantify the Energy Flexibility at the building cluster scale. A novel definition of building cluster and its possible different levels of connections have been outlined, and first steps towards a definition of Energy Flexibility at a cluster scale have been set. The reviewed indicators have been classified into different categories related to cost, thermal and electric features, cluster composition and smart readiness. The outcomes of the study can actively contribute to the development process of the Smart Readiness Indicator (SRI) introduced in the European Commission proposal for amending EPBD, by supporting the assessment of smart technologies and strategies for building readiness improvement in demand response. The work is intended to be a starting point for future research and an overview for policy makers that will have to deal with the new topic of Energy flexible building clusters.

Acknowledgments

This work is part of the research activities of the International Energy Agency - Energy in Buildings and Communities Program Annex 67, Energy Flexible Buildings. The activities are carried out in the framework of the project INTEGRIDS funded by the European Regional Development Fund ERDF.

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