IEA EBC Annex 67

Literature review on energy flexibility definitions and indicators for building clusters

A technical report from IEA EBC Annex 67 Energy Flexible Buildings

Literature review on energy flexibility definitions and indicators for building clusters

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Summary

The introduction of the capacity of Smart Buildings, able to both consume and produce energy, have changed the relation between the buildings and the energy infrastructure: the paradigm is shifting from single energy efficient units to interconnected active players that manage the energy flows.

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.

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.

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

Finding a common definition for 'building cluster' concept is the starting point necessary for setting 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, even if there is not a univocal description of clusters' features.

In particular, 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. 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. 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.

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.

Starting from the previous reviews, a new definition of cluster is suggested and adopted within Annex 67: ***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* enables the management of the building cluster by a common agent or company who can potentially exploit the Energy Flexibility of the whole cluster. 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 Distribution System Operator (DSO), offering in exchange a reduction of the energy consumption when required by the grid.

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, 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 identified auxiliary concepts 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 working 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.

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 the 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, focuses on single buildings, and there are no specific indicators for clusters. Within this report, we identified 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:

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.

Contents

1. Introduction

The “Clean Energy for All European proposals” (EC, 2016a) of European commission sets out the energy policy framework until 2030 and it 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.

Renewable energy systems are characterized by intermittent generation and their rapid increase challenges the stability of the electrical grid (Whiteman, Rinke, Esparrago, & Elsayed, 2016). A mitigating effect of the stress put on the grid by RES 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 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, partly due to rigid regulatory frameworks or 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 expansive for massive application. Consequently, the produced renewable electricity is often injected in the public network instead of being used locally. Therefore, it is necessary to identify solutions aimed to change the relationship between the grid and the consumers and 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 the past recent years, a deep evolution of the building design approach in terms of targets, technology functions, overall performances and domain has occured. In this regards, the improvement of buildings resilient behavior coupled with grid interaction represent the latest step in the evolutionary path of building transformation (Fig. 1). The process, started with the minimization of the energy demand through passive building solutions (passive buildings), which evolved into the nearly Zero Energy Buildings (nZEB) aimed at obtaining an energy balance (consumption-production) through on-site generation from RES, will now find its latest evolution in the energy matching required by smart buildings at the cluster/energy infrastructure domain.

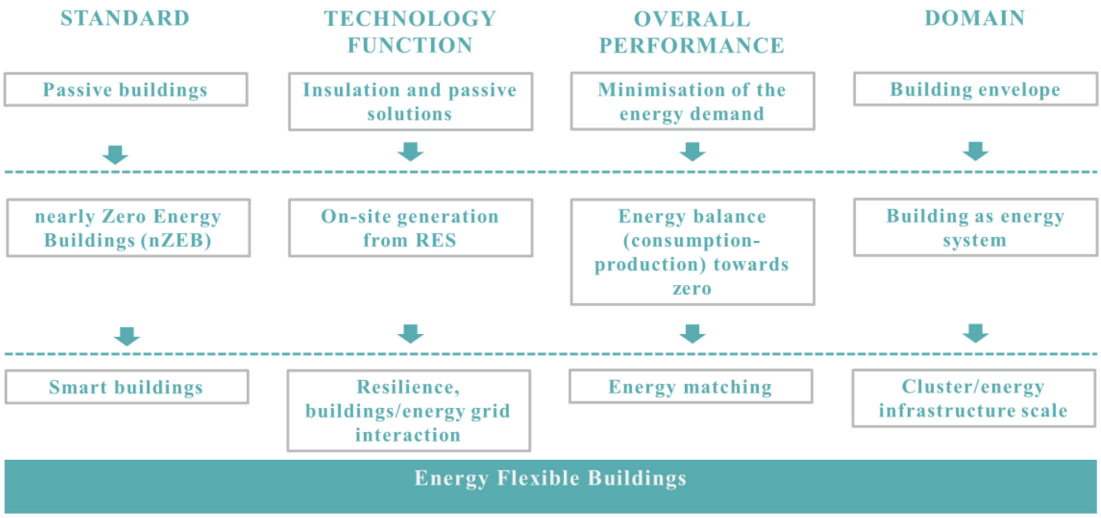

Figure 1. Evolutionary path of building transformation.

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, 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, minimizing their effects in a given time interval. The forcing factors represent a set of significant boundary conditions that could change during the life-time of a building and they can have different levels of frequency:

- *Low frequency*: climate change, macro-economic factors, technological improvement and building intended use;
- *High frequency*: internal loads, solar loads, user behavior, and 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 the user behaviour on an Energy Flexible Building. One of the issues faced within this Annex is the assessment of the Energy Flexibility at cluster level. It is meant to be an intermediate level between 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 report aims to make a comprehensive overview of the theoretical approaches, currently described in literature, for the evaluation of Energy Flexibility of building cluster in order to provide the framework for the performance assessment of the future generation of Energy Flexible buildings. In particular, the section *Energy Flexible Building Clusters* clarifies the importance of designing at cluster scale, then explains the meaning of the word ‘cluster’ (definition) in order to identify its specific features, the working scale (composition) and the level of interaction among buildings (connection); the chapter *Definition of Energy Flexible Building Clusters* reports some key concepts adopted so far in literature to describe the synergy of energy efficient buildings and renewable energy utilization at aggregated level; the section *Reviewed Energy Flexibility indicators for building clusters* focuses on existing metrics and indicators that can be used to quantify Energy Flexibility at cluster scale.

2. Towards Smart Readiness Indicator

In the development process of 'smarter buildings' able to improve energy efficiency and user comfort, the spread of information to consumers on operational energy consumption can contribute to RES maximization at local level. According to 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 gives as key SRI functionalities: (i) the technological readiness assessment of buildings capacity to adapt according 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 may increase building user's consciousness on the fundamental role of smart technologies and ICT solutions, encouraging the creation of more healthy and comfortable buildings with a lower energy use and carbon impact, and can facilitate the integration of RES.

The current state of discussion at 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 to a building, by using measured physical data and results from simulation campaigns. So the approach that is going to be defined within 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 to a building (Østergaard Jensen et al., 2017).

In order to properly process to create the SRI indicator, the identification of smart services and smart technologies is essential and the concept of 'functionality levels' can be introduced to value the smartness of a service implementation, ranging from basic functionality to fully integrated smart solutions (Fig. 2) (Verbeke, Ma, Bogaert, Tichelen, & Uslar, 2017).

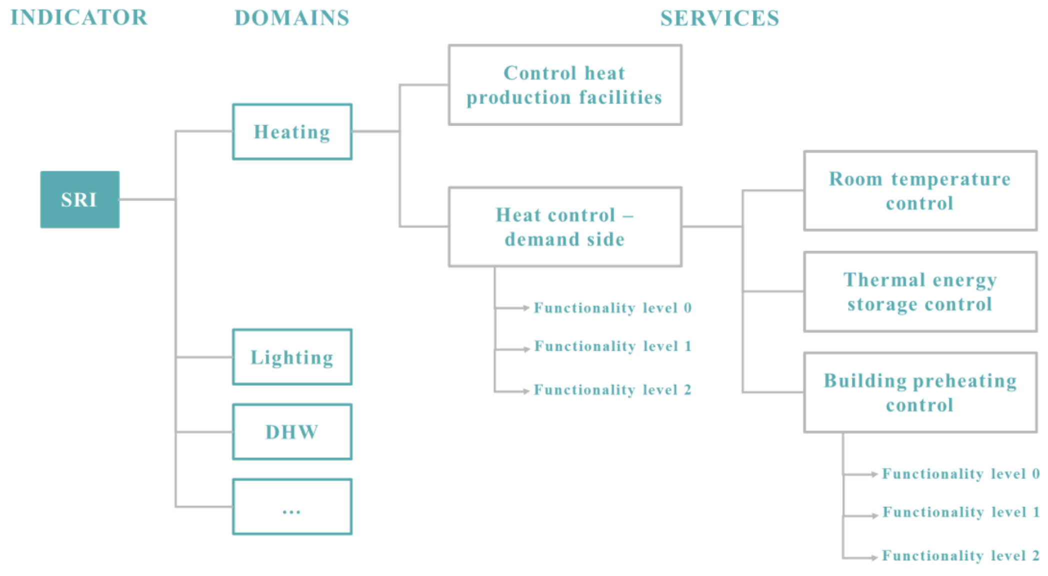

Figure 2. Excerpt from structure of the service list (Verbeke et al., 2017).

The review and investigation of Energy Flexible indicators can contribute to define the proper smart technologies 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). The consequent upscaling to building cluster allows to exploit the variation in energy consumption patterns between different types of buildings (e.g. commercial and residential) and to coordinate load shifting to improve renewable energy use within the community.

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, technologies and strategies to increase energy efficiency and minimize the CO_2 emissions, operational life time and possible changes in building use, energy markets and climate conditions.

Considering energy performance of buildings at aggregated level can lead to several benefits in terms of increased efficiency, higher possibilities of storage and load complementary due to building usage differences, and compensation of particular constraints that could affect one single building - e.g. the poor energy performance of a not-retrofitted historic building can be balanced by the high efficiency of closer new buildings.

3.2 Definition of building clusters

The investigation of '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. In fact, in literature it is possible to find several terms and definitions related to the cluster concepts according to different perspectives, but there is no a univocal description of the features of a cluster.

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

The focus on 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 clusters 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 reduce 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 high 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).

3.3 Composition of building clusters

The design of a building cluster does not have a defined template and it can be composed by a highly variable number of buildings. As emerged from the study of Maïzia et al. (Maïzia et al., 2009), the morphology of the district influences energy demand and the possibility to jointly reasoning at building cluster scale and energy distribution grids can improve the management of energy flows and the RES energy production.

In this regards, it is important to cite the energy performance comparison carried out by Marique and Reiter, 2014 between a Belgian high-density neighborhood (60 dwellings per hectare) situated in the proximity of services, and transport systems (Fig. 3) and a low-density neighborhood (5 dwellings per hectare) composed of terraced houses located in the city suburbs (Fig. 4). A comparison shows that more compact urban forms significantly reduce energy consumption both in the building and transport sectors, despite a lower RES availability from photovoltaic due to a higher shadowing effect.

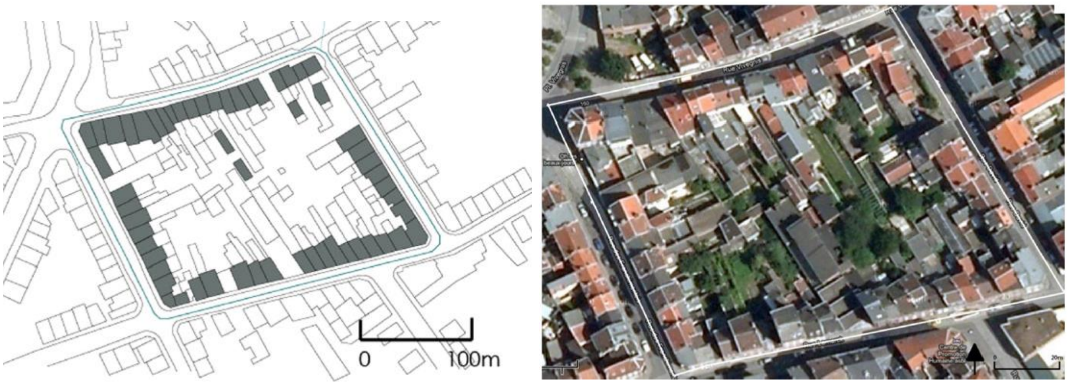

Figure 3. A representative urban residential dense neighborhood, Belgium. Map of the village left). Street view right) (A.-F. Marique & Reiter, 2014).

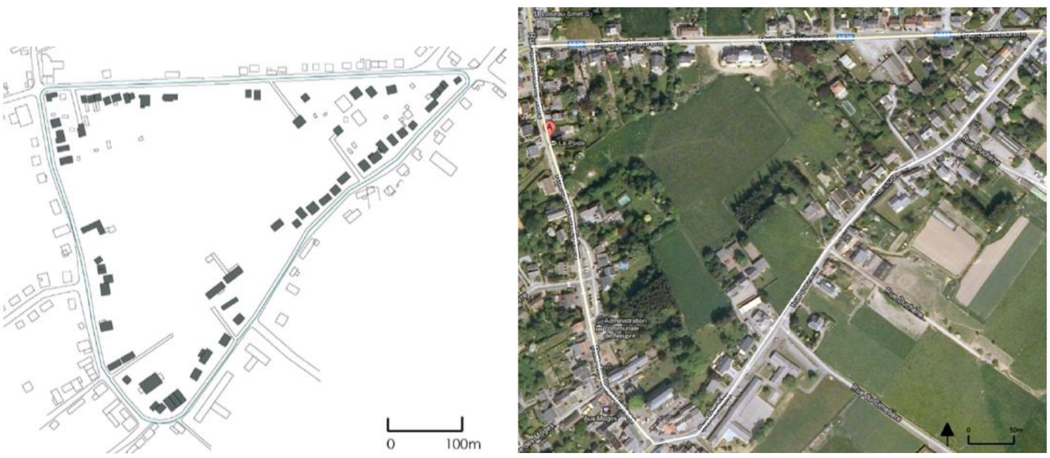

Figure 4. A representative suburban residential neighborhood, Belgium. Map of the village left). Street view right) (Marique & Reiter, 2014).

Another case, investigated by He et al., 2016, is the Historic Green Village located in Anna Maria Island, Florida (Fig. 5); this virtual Net Zero Energy Community testbed consists of 5 mixed-use - retail, residential and office - buildings, supplied by three renewable energy sub-systems coupled with each other: an electric energy system powered by PV panels, a water-source heat pump system and a solar thermal domestic hot water system. The study highlighted that the mixité is an important parameter for energy efficiency improvement, because buildings with different functions and different occupancy patterns have varying load profiles that can be balanced and flatten across a community, due to different time-of-use-rates.

Figure 5. Historic Green Village on Anna Maria Island, Florida. Building layout left). Street view right) (He et al., 2016).

The study of Orehounig et al., 2015 applies the energy hub concept at neighborhood level on the Zernez village in Switzerland (Fig. 6) composed of 29 different buildings - from historically protected constructed before 1900 to new buildings from the year 2000 - connected with a small district heating network. The composition parameter of mixed-age highlights the importance of reasoning at cluster scale for energy performance improvement, because the poor energy performance of historic buildings without retrofitting can be easily compensated by the one of new energy efficient buildings.

Figure 6. Village of Zernez, Switzerland. Map of the village left). Street view right) (Orehounig et al., 2015).

From the reviewed case studies it emerges that there is not a definite number of buildings to describe a cluster. Nevertheless, considering that the scale of the project is an intermediate level between single building and the city, it is possible to affirm that the proper composition of a building cluster overlaps with that one of the quartier, consisting of a small number of energy interconnected buildings able to provide renewable energy production. According to the analysis of the previous case studies, the design solutions, that should be applied to improve the energy efficiency of the cluster, has to consider the *high density* and *mixité of usage* and *age construction*.

3.4 Connection within a building cluster

In the framework of Annex 67, it was decided to consider clusters as composed by different buildings, which can be either physically connected or market aggregated. The physical connection includes any means that 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 sources toward the buildings (e.g. district heating). This type of arrangement may be related to a single utility customer - *aggregate net metering* - or multiple utility customers - *community net metering* - that supply several contiguous buildings with a single on-site renewable energy system (Barnes, 2013).

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

4. Definition of Energy Flexible Building Cluster

One of the specific objectives of Annex 67 is the development of a common definition of 'Energy Flexible Building Clusters', in order to create a common basis for the work and to explain what Energy Flexibility is and how it can be evaluated. The absence of a consolidated definition required as starting point the analysis of some auxiliary concepts adopted so far in literature to describe the synergy of energy efficient buildings and renewable energy utilization at aggregated level; all these concepts contain important keywords that will be included in the final definition elaborated by Annex 67.

The definition of Energy Flexible Building Clusters can be explained through the following auxiliary concepts: (i) *Smart Building Clusters* and (ii) *Zero Energy Neighbourhoods* stressing the role of smart interaction between buildings and grid and underlining the importance of reasoning at 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* as 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 social agreement of users about sharing their energy sources.

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 running 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 markets, buildings and infrastructure technologies, as well as in the EU legislative framework.

I. Smart Building Clusters

The concept of Energy Flexibility at an aggregated level can be linked to the definition of "*Smart Building Clusters* (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 use of local renewable energy, a decrease in electricity prices, 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 Neighborhoods

The "Zero Energy Building" concept still considers the individual building 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 forms, building energy needs and on-site production of RES (Marique & Reiter, 2014), in order to balance annual building energy consumption and individual transportation by the local production of renewable energy (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 hub 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 resources (DERs) 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).

5. Reviewed indicators for evaluating Energy Flexibility at 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 in order to reduce demand peaks in buildings. Indicators are also a way to effectively communicate the energy flexibility concept, enabling the share of 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, only focuses on single buildings. This research identifies a set of potential key performance indicators that can 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:

The *Cost level* focuses on Energy Flexibility quantification with respect to costs.

The *Thermal level* includes:

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

The *Electric level* comprises:

- indicators related to the electrical grid:
- indicators of comfort related to the occupants' satisfaction about indoor artificial lighting.

The *Thermal-electric level* encloses indicators related to cumulative energy demand/supply.

The *Other relevant indicators* section includes indicators related to other auxiliary issues that influences the energy flexibility, such as the influence of typological composition of a cluster on the 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

5.1 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 cluster scale, multiple cost curves, as can be seen from the Fig. 7, can be aggregated and for every point on the cost curve it is possible to obtain the ***specific cost of flexibility*** c_{sp} expressed in c€/kWh. The Specific Cost of Flexibility indicator is calculated as the ratio between the extra cost that follows from the load shifting ΔC [c€] and the amount of electricity ΔE [kWh] that can be shifted out in comparison to the reference scenario (Equation 1).

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

Equation 1

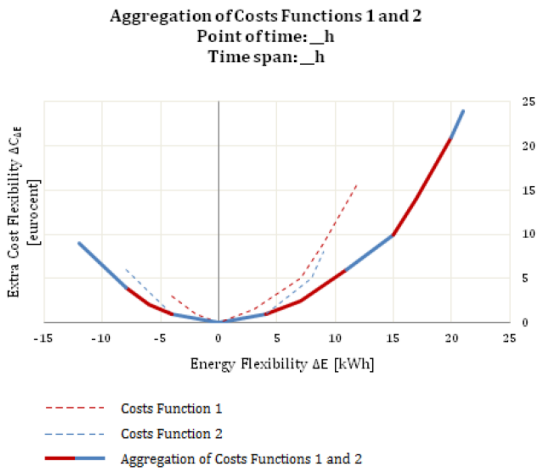

Figure 7. Aggregation of two cost functions. (De Coninck & Helsen, 2013)

The study of Piacentino et al. (Piacentino & Barbaro, 2013) introduces two further indicators that can be applied at cluster scale, the Spark Spread and the Total Supply Spread, to express the convenience in self-producing heat and electricity compared to energy purchase from the public grid. The ***Spark Spread*** (*SS*) is defined as the "ratio between the market price *MPe* 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):

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

Equation 2

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

Compared to equation 2, the third 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 recovered 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" (Equation 4). A null value indicates that the heating use is similar in low and high periods, a positive unitary value expresses that heating is not used in high price periods and finally a negative unitary value means that no heating is used in low price periods. This indicator explains how the load is distributed compared to the peaks but it doesn't give any information on how much load can be shifted.

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

Equation 4

5.2 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} indicating the duration of the 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} 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 resulted from the cooling supply time failure of an 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.

5.3 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 the users;
2) "second priority loads" are reschedulable usage loads of appliances that use a 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 dishwashers, clothes washers 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

θ1, θ2, and θ3 represents 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 and 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 indicator can be expressed in function of load metering (Equation 8) or net metering (Equation 9), while the presence of on-site battery modifies the index (Equation 10) by adding the battery energy balance 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 index 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 the absolute value of the maximum of an annual cycle” (Equation 11).

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

Equation 11

5.4 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 aggregating energy production and consumption of different types of buildings. 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 annual energy supply from local renewable energy sources.

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 to 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 overall supplying more than its demand will be characterized by high values of OER and MHS, while the case of low OER and high MHS implies that the RES supply of the cluster is not optimally planned.

The role of local storage in the ratio between load and RES on-site generation in a cluster can be taken into account 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 biggest and the 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).

5.5 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 a high 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 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 is 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 aggregated level.

6. Conclusion

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 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 IEA EBC Annex 67, a literature review was conducted to describe the characteristics of building clusters and existing available indicators to quantify the Energy Flexibility at building cluster scale. The specific characteristics of an Energy Flexible Building Cluster have been outlined - meaning of the word 'cluster' (definition), working scale (composition), different levels of interaction among buildings (connections) - and 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 research 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 starting point for the future research and an overview for policy makers that will have to deal with the new topic of Energy flexible building cluster.

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