Africa-Europe Bioclimatic Collaboration 21

Africa-Europe BioClimatic buildings for XXI century

REPORT ON ENERGY FLEXIBILITY INDICATORS, WITH FOCUS ON WARM CLIMATE CONDITIONS

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ABC 21 project

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Executive Summary

This report aims to describe the concept of flexible building though a critical review of the main methodologies, definitions and indicators available in literature and international standards (not easily accessible and familiar to those outside academia).

The main report findings are summarized as follows:

- The term “flexible building” is defined in different way depending on the research environment and target group. The lack of international uniformity for the requirements and properties of an energy flexible building leads to numerous definitions that are being developed in parallel. This discrepancy is even more noticeable for the quantification methodologies. However, all definitions recall the basic concept that energy flexibility represents the ability of a building to adapt its energy consumption to provide specific services. A dedicated study on flexibility in buildings has been developed by the IEA EBC Annex 67 project “Energy Flexible Buildings”. They propose a more comprehensive definition, which states as follows: *“the Energy Flexibility of a building is the ability 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”.*

- The evolution torwards energy flexible buildings can be summarized as in the following table:

Target	Technology function	Overall performance	Domain
Passive buildings	Passive solutions	Minimisation of the energy demand	Building envelope
nZEB	On-site generation from RES	Energy balance towards zero	Building as energy system
Flexible buildings	Resilience buildings and energy grid interaction	Energy matching	Cluster

- A review about **flexibility existing metrics** in terms of the characterization, quantification and assessment methodology available in literature was carried out. An extract of the analysis is reported as follow:

Ref	Quantification	Type of climate	Case studied	
			TES	System
Oldewurtel et al. 2013 (*)	Flexibility quantified by efficiency curves, depicting the maximum power increase or decrease against the power shifting efficiency	Case study location: Basel, Switzerland (Dfb climate)	Passive	Heating system that uses building’s thermal mass
…	…	…	…	…

- A set of **Key Performance Indicators** (KPIs) to evaluate the energy flexibility of buildings is provided. An extract of the KPIs set is reported below:

REF	Index name	FORMULA	Description	Methodology	H/C	CC	Comment
Oldewurtel et al. 2013	Power Shifting Potential	$\Delta P(s_i) = P_i(s_i) - P_i(s_0)$	Power Shifting Potential ΔP of the building for providing a grid service at hour *i*, i.e., the amount of power the building can deviate from the baseline power consumption if needed.	Simulation-based	Both	Dfb	These indicators suit systems configuration connected to the electricity grid.

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	Power Shifting Efficiency (PSE)	$\overline{PSE}(i) = \frac{\Delta P(s_{-i})}{\Delta E_T(s_{-i})} \quad for\ i = 1, \dots, 24$	Power Shifting Efficiency is the ratio of the maximum possible change in power consumption at an hour *i* to the additional energy consumption over a test period T necessary to deviate from energy-optimal trajectory. This deviation from the energy-optimal baseline will incur some costs.				In order to use these indicators, they need to be appropriately adapted to the case study
Le Dréau and Heiselberg 2016	Flexibility Factor	$Ff = \frac{\int_{low\ price\ time}(q_{heating})dt - \int_{high\ price\ time}}{\int_{low\ price\ time}(q_{heating})dt + \int_{high\ price\ time}}$ $\Delta q_{heating} = q_{heating\{modulated\ SP\}} - q_{heating\{constant\ SP\}}$ $\Delta Q_{heat\ discharged} = \int_0^{\infty} \Delta q_{heating}(\Delta q_{heating} < 0)dt$ $\Delta Q_{heat\ charged} = \int_0^{\infty} \Delta q_{heating}(\Delta q_{heating} > 0)dt$	The flexibility factor illustrates the ability to shift the energy use from high to low price periods. - If the heating use is similar in low and high price periods, the factor is 0. - If no heating is used in high price periods, the factor is 1. - If no heating is used in low price periods, the factor is -1	Simulation-based	Heating	Dfb	These indicators have been developed for a heating scenario. In order to use these indicators, they need to be adapted to the cooling scenario.
…	…	…	…	…	…	…	…

- Indicators available in literature can be grouped according to three metrics: the quantity of energy that can be shifted; the temporal flexibility, i.e., how long the consumption can be shifted; the cost of utilising this flexibility.
- It is worth highlight that the literature analysis shows a lack of insights into indicators and example of application related to cooling dominated climates. Further, some indicators are very complex and require many input data which are difficult to be collected (especially in the absence of a proper building energy management system).

Acronyms

Term	Name
BAB:	Building As a Battery
BACS	Building automation and control system
BES	Building Energy System
BMS	Building Management System
CHP	Combined Heat and Power production
DHW	Domestic Hot Water storage
DR	Demand Response
DSM	Demand-Side Management
GI	Grid Interaction
HP	Heat Pump
HVAC	Heating Ventilation and Air-Conditioning
ISO	Independent System Operator
LF	Load Shifting
LM	Load Matching
PCM	Phase Change Materials
PPD	Peak Power Demand
PV	Photovoltaic
RES	Renewable Energy Sources
RTP	Real Time Pricing
SOC	State Of Charge
TES	Thermal Energy Storage
TOU	Time Of Use
ZEB	Zero Energy Building

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1. Introduction

In recent years, the construction industry has been comprehensively focusing on the energy performance of buildings and on achieving higher standards of living comfort. One of the most sophisticated ways to attain both at the same time is (re)achieving building's climate balance by using bioclimatic design [2]. Buildings designed based on bioclimatic architecture are more sustainable, have a healthier indoor environment, are more comfortable and have improved energy efficiency, which ultimately leads to lower energy costs [3].

ABC 21 aims to increase the energy performance, the quality of life and sustainability of West-African buildings through the identification, strengthening and effective deployment of affordable bioclimatic designs and local materials under the challenging African climate and urbanization context.

The necessity to move rapidly towards a large share of renewables within the energy mix implies, due to their time variability, the need for buildings to be flexible in the time when they require energy. This is a new design constraint that should be fully integrated with an updated bioclimatic approach. Thermal inertia of buildings, if compatible with local climate and together with other features like dedicated energy storages, might constitute one of the important options to achieve flexibility. This latter has several dimensions (e.g. peak reduction and peak shifting in terms of power, shifting in terms of amount of energy and time lag).

This deliverable aims to investigate the topic of energy flexibility with a focus on warm climates and bioclimatic buildings. It reviews the main approaches, models, definitions and tools available in literature and international standards but not easily accessible and familiar to those outside academia. It provides information for buildings located both in Europe and Africa, specifying the most appropriate methods to assess flexibility for each context.

After this overview, the report provides a list of Key Performance Indicators (KPIs) to determine energy flexibility of a bioclimatic building.

A careful selection of these indicators based on the climate type will be done in the next phase of the project in order to assess and compare the case studies examined in Task 3.4 – Case studies of European and African Bioclimatic buildings, some of which will be evaluated in a simulation environment while others through in-situ measurements.

2. Nomenclature and definitions of energy flexibility in buildings

The following list shows the common definitions and nomenclature regarding energy flexibility in buildings stated by international standards.

- **Baseline**: a method of estimating the electricity that would have been consumed by a customer or demand resource in the absence of a demand response event. It may be calculated using interval metering and/or statistical sampling techniques.
  (ISO 17800:2017 Facility smart grid information model) [4]
- **Building Management System**: computer-based control system installed in a building that controls and monitors mechanical and electrical equipment such as heating, ventilation and air-conditioning (HVAC), power systems and access control systems.

(ISO/IEC 18598:2016 Information technology — Automated infrastructure management (AIM) systems — Requirements, data exchange and applications) [5]

- **Demand resource**: a load, aggregation of loads, behind-the-meter generator, electrical storage system, or thermal storage system capable of providing measurable and verifiable demand response.
  (ISO 17800:2017 Facility smart grid information model) [4]
- **Demand response**: method for matching the demand for energy to the available supply of energy.
  (ISO/IEC 15067-3:2012 Information technology — Home Electronic System (HES) application model — Part 3: Model of a demand-response energy management system for HES) [6]
- **Demand-Side Management**: utility programs developed to influence the customer demand for power in order to align with the available supply
  (ISO/IEC 15067-3:2012 Information technology — Home Electronic System (HES) application model — Part 3: Model of a demand-response energy management system for HES) [6]
- **Electricity grid**: electricity supply network
  (ISO/IEC 15067-3:2012 Information technology — Home Electronic System (HES) application model — Part 3: Model of a demand-response energy management system for HES) [6]
- **Energy management system**: a system used to monitor and control the energy consuming devices in a building. Within this standard, "energy management system" always refers to a customer/facility energy management system and not a utility energy management system.
  (ISO 17800:2017 Facility smart grid information model) [4]
- **Grid interaction**: refers to the energy exchange between the building and a power grid.
  (Salom et al. "Understanding net zero energy buildings: evaluation of load matching and grid interaction indicators." In 12th Conference of International Building Performance Simulation Association, 9. Sydney, 2011.) [7]
- **Load matching**: refers to how the local energy generation compares with the building load (intended as gross load or energy use).
  (Salom et al. "Understanding net zero energy buildings: evaluation of load matching and grid interaction indicators." In 12th Conference of International Building Performance Simulation Association, 9. Sydney, 2011) [7]
- **Load Shifting**: is a load management technique that aims to move demand from peak hours to off-peak hours of the day. Loads are shifted from peak to valley times (achieving clipping and filling).
  (Kumar et al. Handbook of Research on Power and Energy System Optimization. Handbook of Research on Power and Energy System Optimization, 2018) [8]
- **Peak demand**: The highest measured demand encountered during a specified period of time (e.g., month, year, or finite set of time intervals).
  (ISO 17800:2017 Facility smart grid information model) [4]
- **Peak load**: the maximum amount of power delivered (load) for a given time period.
  (ISO 17800:2017 Facility smart grid information model) [4]
- **Peak shaving**: reducing the peak in the required cooling power, so that it is possible to cool the structures of the building during a period in which the occupants are absent (during night time) the maximum amount of power delivered (load) for a given time period.
  (ISO 11855-4:2021 Building environment design — Embedded radiant heating and cooling systems — Part 4:Dimensioning and calculation of the dynamic heating and cooling capacity of Thermo Active Building Systems (TABS)) [9]
- **Smart Grid**: electric energy distribution system using information and communications technology with automation for improving the stability and availability of electricity

- Note1: Some smart grids integrate into the electric grid excess power generated locally from sun and wind-driven devices.
- Note2: Technically, a grid is a network. However, in common usage the term “smart grid” refers to the entire energy system, which include generation, transmission, distribution, and customer systems.

(ISO/IEC 15067-3:2012 Information technology — Home Electronic System (HES) application model — Part 3: Model of a demand-response energy management system for HES) [6]

- **Thermal mass**: materials with mass heat capacity and surface area capable of affecting building loads by storing and releasing heat as the interior and/or exterior temperature and radiant conditions fluctuate

  (ISO 16818:2008(en) Building environment design — Energy efficiency — Terminology) [10]

- **Time of use pricing**: a rate structure characterized by different prices for electricity use in a 24-hour time frame. Time of use pricing is generally used to encourage electricity use during periods of lower demand and discourage electricity use during periods of high demand.

  (ISO 17800:2017 Facility smart grid information model) [4]

3. State of the art on energy flexibility in buildings

Energy flexibility in buildings is increasingly being discussed in relation to the growing electrification and penetration of non-dispatchable renewable energy sources (RES), such as solar power and wind power, into the energy system. In order to adapt to the needs of the network and to RES production, buildings and districts needs to make flexible their energy consumption, while maintaining adequate indoor comfort conditions for the occupants.

The concept of energy flexibility of buildings originates from the demand side management regime which proposed different strategies to improve the load profile shape such as the reduction of the energy demand at peak periods (peak clipping or peak shaving), the shift of the energy consumption from periods where RES are scarcely available to times of high RES feed-in (load shifting), the increase of energy use during off-peak times (valley filling), demand-response programs.

Many researchers are focusing their studies on the topic of energy flexibility at the building [11] and, more recently, cluster of buildings level [12], proposing methodologies and indicators to quantify this potential. The majority of the studies on energy flexibility has been developed considering heating dominated climates and analysing the different ways of obtaining energy flexibility, mainly through dynamic simulations. In contrast, the bibliography regarding flexible buildings in tropical/hot regions is poor.

The evolutionary path of building design (Figure 1) has started with the concept of *passive building*, passing through the *nearly ZEB* concept, to reach its latest evolution with the *smart building* which is characterized by the ability to adapt in response to the occupant’s needs, to facilitate maintenance and efficient operation and to adapt in response to the needs of the grid. Energy flexibility is seen as a key asset in the smart building future, as emphasized by the recent development of the European Smart Readiness Indicator for buildings.

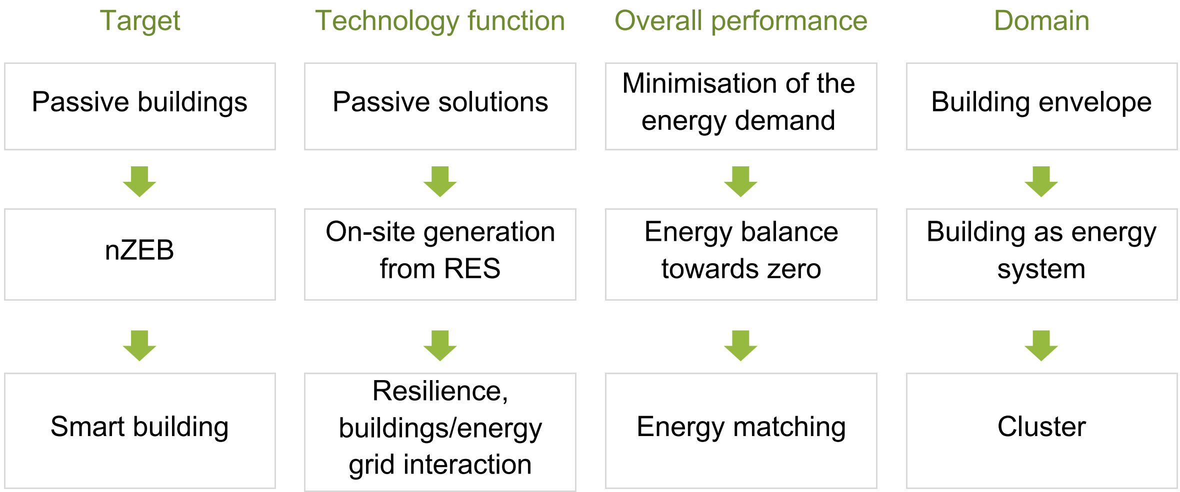

Figure 1: evolutionary path of building transformation – adapted from [12]

Energy flexibility is also linked to the concept of Smart Grid (or Smart Energy Network) where both demand and local production are controlled to stabilize the energy networks and thereby lead to a better exploitation of the available renewable energy sources towards a decarbonisation of the building stock. Buildings are, therefore, expected to have a pivotal role in the development of future Smart Grids/Energy networks, by providing energy flexibility services. Table 1**Error! Reference source not found.** summarizes the main differences between a traditional grid and a smart grid approach.

Table 1: Building energy system framework overview

Sector	Traditional grid	Smart grid
Market	Centralized	Distributed
Production	Traditional power plant	Traditional power plant and/or renewable power plant
Transmission	National grid	National grid and local sub-grid
Distribution	Unidirectional	Bidirectional
Consumer[1]	Passive user	Passive and active user

It is worth highlighting that, in case of bioclimatic architecture, the boundary conditions must be revalued (i.e. if the building is not connected to the grid).

In this framework, project ABC 21 aims to investigate the approach to energy flexibility in buildings in warm climates discussing if it's possible to extend its application to the target of bioclimatic buildings and quantify its potential.

[1] In the case of bioclimatic architecture unprovided of any type of systems, the boundary of energy flexibility action regards solely the consumer, the building fabric and how they use it.

3.1. Demand side management

Energy flexibility of a building is really not a new concept. It originates from the demand side management (DSM) regime, which for decades has been applied by the designers and operators to foster stable and bottleneck-free operation of the electrical energy systems.
DSM is the modifiction of consumer demand for energy through various methods such as financial incentives and behavioural change through education.
DSM improves load profile shape, maximizes the over all infrastructure utilization and also minimizes the over all system cost with the help of controllable loads
In literature are reported six basic load shaping methods (Figure 2): peak clipping, valley filling, load shifting, strategic conservation, strategic load growth and flexible load shape [13].

DSM technologies can be used to activate the energy flexibility of buildings [14]. They can be divided into three main categories: (i) energy-efficient end-use devices; (ii) additional equipment, systems, and controls to enable load shaping (e.g., energy storage); and (iii) communication systems between end-users and external parties, for example, demand response (DR) programs.

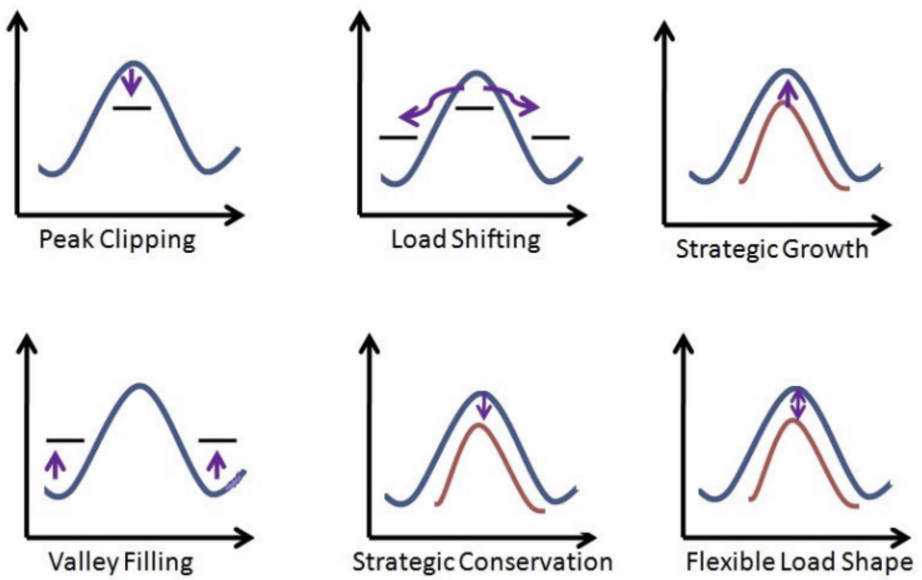

Figure 2 DSM load shape methods [13]

3.2. Definition of energy flexibility

Most of the studies start from the concept that energy flexibility implies the ability to shift energy, from few hours to a certain number of days, without jeopardizing technical and comfort constraints. The term “flexible building” has been defined in different way depending on the research environment and target group which has led to numerous definitions that have been developed in parallel [1]. This discrepancy is even more noticeable for the quantification methodologies. However, all definitions recall the basic concept that energy flexibility represents the ability of a building to adapt its energy consumption to provide specific services.
A dedicated study on flexibility in buildings has been developed by the IEA EBC Annex 67 project “Energy Flexible Buildings”. They propose a more comprehensive definition, which states as follows: *“the Energy Flexibility of a building is the ability 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" [11].

3.3. Energy flexibility in the European perspective

Considering the transition towards clean energy, for the European commission energy flexibility represents a key issue to be achieved. The interaction between buildings and the actors involved within the grid (i.e. consumers, producers, national electricity supplier) can contribute to RES maximization at local level. In particular, the 2018 revision of the European Energy Performance of Buildings Directive (EPBD) [15] introduces a voluntary scheme for rating the smart readiness of buildings called "Smart Readiness Indicator" (SRI) which clearly states among the key functionalities of smart buildings the capability to adapt to signals from the grid (e.g. energy flexibility). The detailed SRI methodology is reported within section 4.5.1. The introduction of such assessment methodology will increase consumers' consciousness and promote low carbon impact buildings and healthier and more comfortable environment, while facilitating RES integration. The EU is currently evaluating the building flexibility though a qualitative approach by means of the counting of features and components, on the contrary to Annex 67 which will provide a quantitative characterization by using measured physical data and simulations campaigns [12].

3.4. Sources of energy flexibility in buildings

There are different ways to obtain energy flexibility in buildings (Figure 3):

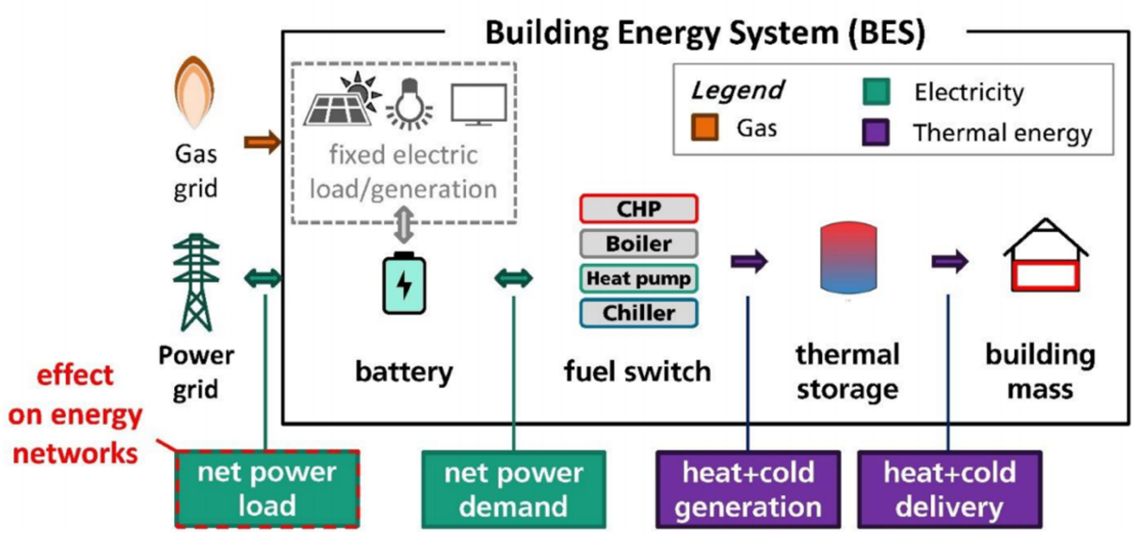

Figure 3: Strategy involved for the exploitation of energy flexibility [16]

- **Building As a Battery (BAB) – Using building's thermal mass for efficient energy management**
  Building components, which are characterized by a certain thermal capacity, can be used to store energy when the demand is low and energy from RES is available in order to reduce its request during peak periods.
  The strategy is based on accumulating heat (e.g. in winter) by increasing the building set point indoor temperature to allow a subsequent complete switch off of the system for a certain period when RES are not available or during peak periods. The action

duration depends on various factors (including thermal features and external climate) but can vary from a few hours to some days. High performing envelopes can contribute to extend the period during with the system is not active without jeopardized thermal comfort [17].
The advantage of this type of storage is that it is normally considered to be cost-free since is already part of the building fabric. But, on the contrary, the exploitation of this potential is strictly related to users' preferences and acceptability and to the installed energy service system and the control of the energy demand in the building technical systems.

- **Building energy loads**

  Three categories of loads can be identified in the building: (1) *shiftable loads*, which can be rescheduled according to the Penalty signal (e.g. dishwashers, washing machines, charging devices or electric vehicles); (2) *non-shiftable loads* which are characterized by energy consumption profiles that cannot be modified (e.g. lighting, television and cooking); (3) *other controllable loads,* i.e. shiftable loads that can be adjusted by optimal control strategies (e.g. HVAC units whose consumed energy can be modified by dimming, thermostatic control, and by varying the fan speed)

- **Thermal storage**
  This refers to active systems such as PCM (phase change materials), domestic hot water (DHW) storage and water tanks connected to a heat pump. To obtain the same amount of energy flexibility as the building mass, a large tank is often required.

- **Fuel switch**
  If the building is equipped with different systems powered by diverse fuels (i.e. a hybrid heat pump and an integrated gas boiler), it is better to switch the system (for instance according to electricity price).

- **Battery**
  It's an active energy storage. In a building, different type of battery can be adopted such as the static batteries in the building, the battery of electrical vehicle or the battery of a PV system. The battery is charged during periods with surplus of electricity and discharged when needed.

- **Generation**
  Buildings are becoming prosumers, i.e. able to produce energy through PV, micro wind turbine or CHP (combined heat and power production) plant, beyond consuming energy.

- **Networks**
  A building may be connected to one or more energy networks (e.g. electricity power grid, district heating or gas grid.

3.5. Load match and grid interaction

Two dynamic phenomena are strictly connected with energy flexibility: the load matching and the grid interaction. They are commonly used to represent the temporal energy match in Net Zero Energy Buildings describing the continuous interplay between on-site generation and the building loads, and the resulting import/export interaction with the surrounding energy grid.

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The term load matching (LM) refers to the degree of agreement or disagreement of the on-site generation with the building load profiles; grid interaction (GI) refers to the energy exchange patterns between a building and the utility grid, and its impact on the overall load of the grid (Figure 4) [18]. Energy flexibility is used to improve the load matching and grid interaction performance of the building.

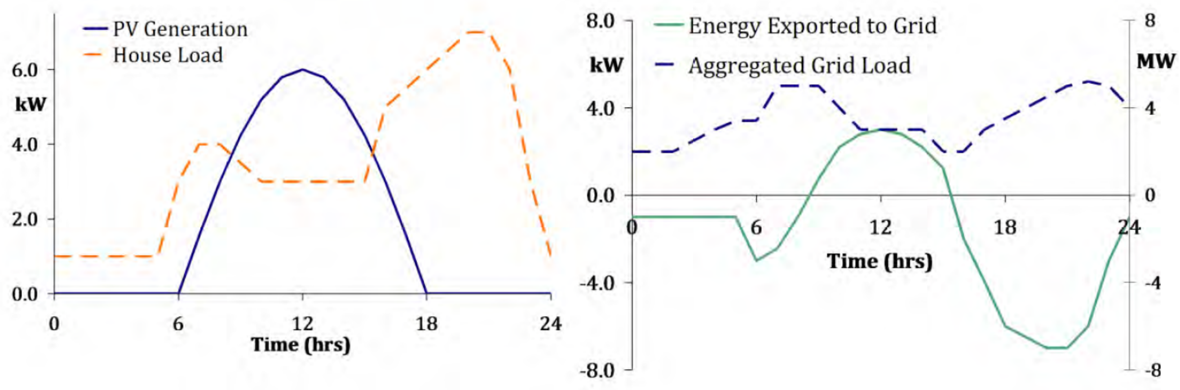

Figure 4 Graphical representation of load matching (left) and grid interaction (right) [18]

3.6. Energy flexibility and resilience

As studied in the final phase of Annex 67 of the IEA EBC Annex 67 Energy Flexibility Buildings [11], to ensure that energy flexibility is fully exploited, some relevant area need to be further explored. Among the identified topics, objectives also of the on-going project IEA EBC - Annex 82 - Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems [19], a new fundamental theme emerges: the resilience.
Flexibility and resilience are strictly related:energy flexible buildings and communities may increase the resilience of the energy networks by reducing the stress on the infrastructure but also make the buildings and communities more resilient to fluctuations in the energy supply [19]. Energy system resilience is defined as “the capacity of an energy system to tolerate disturbance and to continue to deliver affordable energy services to consumers. A resilient energy system can speedily recover from shocks...” [20]. As for flexibility, the need for resilient building design and construction is fundamental to anticipate climate change and disruptions caused by weather extremes, increasing carbon emissions, and resource depletion [21].

Considering the warm climate context, resilient cooling design is an urgent requirement for future proof buildings. According to bioclimatic design, to assume users’ wellbeing it is necessary that weather extremes must be anticipated. Thus, resilient cooling design involves combining passive and active cooling design measures (which should be compliant with comfort model), on-site renewable production, and the coupling to storage capacities [21].

Another crucial aspect, further the technological applications, is the building operation systems which will play a significant role in applying the adaptation strategies and risk mitigation plans in collaboration with buildings users. For resilient cooling, HVAC systems and envelope features are a prime goal for real-time optimization. Different dynamic control strategies with predictive algorithms should be embedded in building operation systems using a deeply coupled network of sensors.

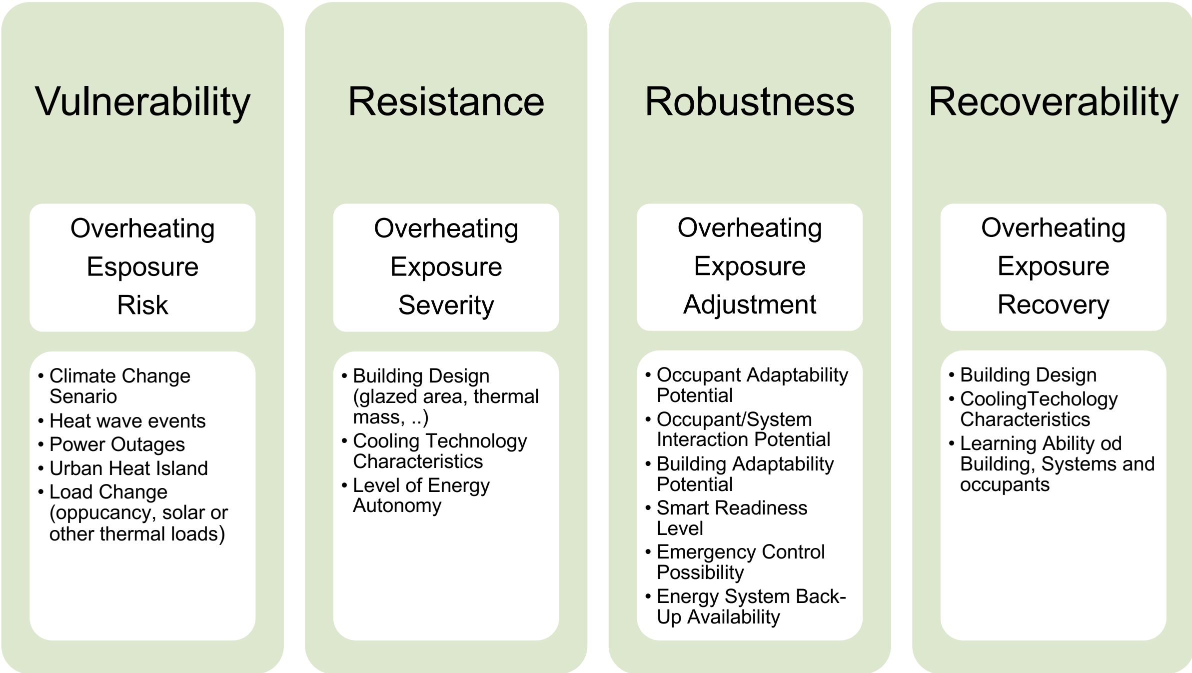

Figure 5: Factors that influence flexibility and resilient cooling of buildings (adapted from [21])

As shown in Figure 5, the resistance phase depends mainly on the characteristics and design technologies of the building and on their ability to maintain the building under severe condition of overheating exposure until reaching failure. Failure is the essential disruption to initiate the third phase of resilience, namely robustness. The robustness of cooling system must adapt to temporally cover the critical thermal conditions until the recovery phase is reached. The ability to respond and apply changes to the original thermal conditions involves occupants and systems adaptability. The presence of energy system backup and an emergency control possibility is part of the building's robustness. This is lastly followed by a recovery stage and a shift in the building performance to achieve the previously designed thermal conditions that reflects adaptation to the normal [21].

4. Flexibility characterization and quantification

4.1. Scope and impacts

The assessment of energy flexibility through indicators is important to quantify the energy flexibility that different types of building can offer, evaluate different technological solutions and control strategies, understand the potential influence of user behaviour and enable a basis for contractual framework between the relevant stakeholders such as end users, aggregators and grid operators. Shared metrics allow also to communicate effectively among the different stakeholders involved in the process.

Energy flexibility could be expressed as power [kW] and/or energy [kWh] that can be shifted - increased or decreased – in reaction to an external signal (within IEA EBC Annex 67 called “Penalty signal”) without jeopardizing the indoor comfort over a certain time span.

Many indicators have been proposed in literature to quantify energy flexibility and the impact that technologies, components or control strategies have on available flexibility. According to IEA EBC Annex 67, they can be divided into two groups:

- “potential indicators” which depend only on the physical/technological properties of the building, describing the amount of energy (defined as potential) that can be shifted (e.g. storage potential);
- “performance indicators” which depends on the specific application, subordinated to the scope and target for which energy flexibility is being applied (e.g. the storage performance will change if the objective of the control is the reduction of CO_2 emissions or the reduction of peak power).

A majority of indicators illustrate how the amount of power or energy during a certain time interval can be altered and how long this defined power increase or decrease can be maintained. Generally, energy flexibility can be defined as the ability to deviate from a reference load profile (baseline power consumption or business as usual scenario) in response to requirements by the operation of the building or the grid.

All indicators addressing load or energy related values are closer to what is useful for the characterization of energy flexible buildings, instead of e.g. price or market related indicators.

4.2. Flexibility quantification methods in literature

An overview of existing flexibility quantification methods in literature is reported within Table 2 with the following terminology:

- the term *passive* stands for the exploitation of buildings’ thermal mass as thermal energy storage;
- the term *active* stands for active storage connected to the mechanical system (i.e. a heating system with a thermal storage tank that is used for space heating and domestic hot water).

Some references are marked with a star (*) since their flexibility indicators are explained more in detail in Table 3.

Table 2: Energy flexibility quantification methods

Ref	Quantification	Type of climate [2]	Case studied	
			Thermal Energy Storage	System
Oldewurtel et al. 2013 [24] (*)	Flexibility quantified by efficiency curves, depicting the maximum power increase or decrease against the power shifting efficiency	Case study location: Basel, Switzerland (Dfb climate)	Passive	Heating system that uses building's thermal mass
Nuytten et al. 2013 [25]	Flexibility quantified by the number of hours the respective energy consumption can be delayed or anticipated.	Case study location: Flanders, Belgium (Cfb climate)	Passive and Active	CHP system with thermal energy storage
Reynders 2015 [26]	Flexibility quantified by the available storage capacity, the storage efficiency and the power shifting potential	Case studies location: Belgium (Cfb climate)	Passive	Heating system that uses building's thermal mass
Masy et al. 2015 [27]	Flexibility is quantified according to the load volumes shifted and the costs avoided during a DR action	Case studies location: Belgium (Cfb climate)	Passive and Active	Heating system that uses building's thermal mass and water tank storage
D'hulst et al. 2015 [28]	Flexibility quantified by the power increases or decreases, combined with how long these changes can be sustained	Case studies location: Belgium (Cfb climate)	Passive and Active	quantified the flexibility offered by five different types of domestic electrical devices
Le Dréau and Heiselberg 2016 [29] (*)	Flexibility is assessed by using a flexibility indicator which quantifies the ability to shift energy consumption away from high price periods	Case studies location: Denmark (Dfb/Cfb climate)	Passive	Heating system that uses building's thermal mass
De Coninck and Helsen 2016 [30]	Flexibility quantified by cost functions, which comprise the amount of energy that can be shifted at a specific time and the associated cost compared to a reference scenario.	Case study location: Bruxelles, Belgium (Cfb climate)	Passive	Heating system that uses building's thermal mass
Stinner, Huchtemann, and Müller 2016 [31]	Flexibility quantified by temporal flexibility, power flexibility and energy flexibility	Case studies location: Germany (Cfb/Dfb climate)	Passive and Active	Heating system with thermal storage tank
Finck 2018 [32]	Flexibility is quantified according to the energy added/curtailed, the associated energy	Case studies location: Netherlands	Active	Water tank, phase change

[2] Koppen climate classification is reported in Annex A

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	costs/savings related to the energy shifted and a factor that determines the electricity cost during operation	(Cfb climate)		material tank integrated with building heating system
Foteinaki et al. 2018 [33] (*)	Flexibility is quantified according to the energy that can be added/curtailed and the associated energy savings/costs during DR events	Case studies location: Danmark (Dfb/Cfb climate)	Passive	Heating system that uses building's thermal mass
Arteconi, Mugnini, and Polonara 2019 [34] (*)	Flexibility is quantified on the response time, the committed power, the recovery time, actual energy variation during a demand response event.	Case studies location: Italy (mostly Csa and Cfa climate)	Passive and Active	Heating/cooling system that uses building's thermal mass and water tank
Liu and Heiselberg 2019 [35] (*)	Flexibility is quantified by means of the ability of power shifting, the efficiency of energy shifting, economic benefits and comfort level.	Case studies location: Denmark, Copenhagen (Csa climate)	Passive	Heating and cooling system that uses building's thermal mass
Erba et al. 2019 [36] (*)	Flexibility is quantified assessing the mismatch between the time of use and the renewable generation	Case studies location: Mascalucia, Italy (Csa climate)	Passive and Active	HVAC system that uses building's thermal mass and active energy storage
Omar et al. 2020 [37] (*)	Flexibility is quantified evaluating solely the building envelope using performance ratios related to the capacity of a building to exploit cooling energy from its thermal mass	Case study location: Djibouti, Africa (Bwh climate)	Passive	No mechanical system
Foteinaki et al. 2020 [38] (*)	Flexibility is assessed by using a flexibility indicator which quantifies the ability to shift energy consumption away from high price and high load periods	Case studies location: Danmark (Dfb/Cfb climate)	Passive	Heating system that uses building's thermal mass
Kathirgamanathan et al. 2020 [39]	Flexibility is quantified according to the energy added/curtailed, and the associated energy costs/savings related to the energy shifted	Case study location: Dublin, Ireland (Cfb climate)	Passive	Heating system that uses building's thermal mass
Zhou and Cao 2020 [40]	Flexibility is quantified according to the respective period during which the energy consumption can be delayed or anticipated (delayed/forced times) by considering the contribution of local RES	Case study location: Hong Kong, China (Cwa climate)	Passive and Active, Batteries	HVAC system that uses building's thermal mass and active energy storage

Lu et al. 2021 [41] (*)	Flexibility is quantified using the following indicators: energy deviation, power deviation, peak power reduction percentage, and energy consumption ratio	Case study location: Beijing, China (Cfb climate)	Passive	Cooling system that uses building's thermal mass
Tang and Wang 2021 [42] (*)	Flexibility is quantified utilizing fast regulation flexibility and load shedding flexibility load shifting flexibility, load covering	Case study location: Hong Kong, China (Cwa climate)	Passive and Active	HVAC system that uses building's thermal mass and active energy storage

4.3. Flexibility indicators in literature

Table 3 shows the flexibility indicators available in literature.

Table 3: Flexibility indicators – literature review

REF	Index name	Unit	Formula	Description	Methodology	Heating / cooling application	Koppen CC	Comment
Oldewurtel et al. 2013 [24]	Power Shifting Potential	[kW]	$\Delta P(s_i) = P_i(s_i) - P_i(s_0)$	Power Shifting Potential ΔP of the building for providing a grid service at hour *i*, i.e., the amount of power the building can deviate from the baseline power consumption if needed.	Simulation-based	Both	Dfb	These indicators suit systems configuration connected to the electricity grid. In order to use these indicators, they need to be appropriately adapted to the case study
	Power Shifting Efficiency (PSE)	[-]	$\overline{PSE}(i) = \frac{\Delta P(s_{-i})}{\Delta E_T(s_{-i})} \quad for\ i = 1, \dots, 24$	Power Shifting Efficiency is the ratio of the maximum possible change in power consumption at an hour *i* to the additional energy consumption over a test period T necessary to deviate from energy-optimal trajectory. This deviation from the energy-optimal baseline will incur some costs.				
Le Dréau and Heiselberg 2016 [29]	Flexibility Factor [-]	[-]	$Ff = \frac{\int_{low\ price\ time}(q_{heating})dt - \int_{high\ price\ time}(q_{heating})dt}{\int_{low\ price\ time}(q_{heating})dt + \int_{high\ price\ time}(q_{heating})dt}$ $\Delta q_{heating} = q_{heating\{modulated\ SP\}} - q_{heating\{constant\ SP\}}$ $\Delta Q_{heat\ discharged} = \int_0^{\infty} \Delta q_{heating}(\Delta q_{heating} < 0)dt$ $\Delta Q_{heat\ charged} = \int_0^{\infty} \Delta q_{heating}(\Delta q_{heating} > 0)dt$	The flexibility factor illustrates the ability to shift the energy use from high to low price periods. - If the heating use is similar in low and high price periods, the factor is 0. - If no heating is used in high price periods, the factor is 1. - If no heating is used in low price periods, the factor is -1	Simulation-based	Heating	Dfb	These indicators have been developed for a heating scenario. In order to use these indicators, they need to be adapted to the cooling scenario.
	Shifting efficiency	[-]	$\eta_{shifting} = \frac{-\Delta Q_{heat\ discharged}}{\Delta Q_{heat\ charged}}$	- In case of *heat storage*, this ratio corresponds to the storage efficiency and is lower than one. - In case of *heat conservation*, the energy use decreases compared to the reference case and the ratio is higher than one				
Shen & Sun, 2016 [43]	Grid interaction index	[-]	$PE_{grid} = STD\left(\frac{Pow_{mis,i}}{max\left[\lvert Pow_{mis,1}\rvert, \lvert Pow_{mis,2}\rvert, \dots, \lvert Pow_{mis,8760}\rvert\right]}\right)$	Grid interaction index quantify the grid friendliness and varies in a range from 0 to 1, a smaller value represents better grid friendliness. - PEgrid is grid interaction index which represents the grid friendliness; - STD is the standard deviation; Powmis is hourly power mismatch representing electrical energy exchange between a NZEB and a grid; subscript i represents ith hour.	Simulation-based	Both	Cwa	These indicators suit systems configuration connected to the electricity grid. In order to use these indicators, they need to be appropriately adapted to the case study
	Comfort Index	[h]	$PE_{comfort} = \sum \tau_i \begin{cases} \tau_i = 1, & if\ CAP_{AC} < CL_i \\ \tau_i = 0, & if\ CAP_{AC} \geq CL_i \end{cases}$	Comfort index is defined as the thermal discomfort coming from the cooling supply time failure of a sized air-conditioning system. - $PE_{comfort}$ stands for 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				
Reynders et al. 2017 [44]	The Available Storage Capacity C_{ADR}	[Wh]	$C_{ADR} = \int_0^{l_{ADR}} (Q_{ADR} - Q_{Ref})dt$	Is defined as the amount of energy that can be added to the storage system	Simulation-based	Heating	Cfb	These indicators have been developed for a heating scenario. In order to use these indicators, they need to be adapted to the cooling scenario.
	The storage efficiency η_{ADR}	[-]	$\eta_{ADR} = 1 - \frac{\int_0^{\infty}(Q_{ADR} - Q_{Ref})dt}{\int_0^{l_{ADR}}(Q_{ADR} - Q_{Ref})dt}$	Is defined as the fraction of the heat that is stored during the A_{DR} event that can be used subsequently to reduce the heating power needed to maintain thermal comfort.				
	The power shifting capability PSC	[s]	$PSC = t_\delta(Q_\delta)$ $Q_\delta = Q_{ADR} - Q_{Ref}$	Is the relation between the change in heating power (Q_δ) and the duration (t_δ) that this shift can maintained, taking into account the future boundary conditions, before the normal operation of the system, i.e. Thermal comfort is jeopardized.				

Foteinaki et al. 2018 [33]	Flexibility Indicators	[kWh]	$Q_{added} = \int (q_{up} - q_{ref})\, dt_{up}$	Added energy (Q_{added}): The amount of energy that is added to the building during the upward flexibility event.	Simulation-based	Heating	Cfb Dfb	These indicators have been developed for a heating scenario. In order to use these indicators, they need to be adapted to the cooling scenario.
		[kWh]	$Q_{discharge} = \int (q_{discharge} - q_{ref})\, dt_{discharge}$	Discharged energy ($Q_{discharge}$): The amount of energy that is utilized after being stored in the thermal mass of the building during the upward flexibility event.				
		[kWh]	$Q_{curtailed} = \int (q_{down} - q_{ref})\, dt_{down}$	Curtailed energy ($Q_{curtailed}$): The amount of energy that is curtailed from the building during the down-ward.				
		[kWh]	$Q_{rebound} = \int (q_{rebound} - q_{ref})\, dt_{rebound}$	Rebound energy ($Q_{rebound}$): The amount of energy that is additionally utilized by the building in order to return to the initial state after the downward flexibility event.				
Arteconi, Mugnini, and Polonara 2019 [34]	Flexibility Performance Indicator	[-]	$FPI = \frac{1}{4}(p_1 t^*_{res} + p_2 \dot{P}^*_{res} - p_3 t^*_{rec} + p_4 \eta_{DR})$ - $t^*_{res} = \frac{t_{res}}{24}$ - $\dot{P}^*_{res} = \frac{\lvert \dot{P}_{res} \rvert}{\dot{P}_{rated}}$ - $t^*_{rec} = \frac{t_{rec}}{24}$ - $\eta_{DR} = \left\{ \begin{matrix} \frac{E_{DR}}{\int_0^{t_{DR}} (\dot{P}_{REF}) dt} & \\ 0 & if\ \ E_{DR} < 0\ \ in\ \ PSS \end{matrix} \right\}$	- The first term is the response time, t^*_{res} Referred to 24 h (p_1=60%). - The second is $\dot{P}^*_{res}$ Normalized to the installed rated power ($\dot{P}_{rated}$) (p2=20%). - The third is t^*_{rec} Normalized on 24 h (p3=10%) - The fourth one is a sort of DR energy efficiency, since it is calculated as the ratio between the actual energy variation achieved during the DR event (E_{DR}) and the building electricity use in reference operation (without DR event) during t_{dr}. It has a weight of 10% (p4=10). The DR energy efficiency is zero if the PSS does not produce any energy saving.	Simulation-based	Both	Csa Cfa	These indicators suit systems configuration connected to the electricity grid. In order to use these indicators, they need to be appropriately adapted to the case study
Aelenei et al. 2019 [45]	Self-Consumption (SC)	[-]	$sc = \frac{\sum_{n=n_1}^{n_2} min(D(n),G(n))}{\sum_{n=n_1}^{n_2} G(n)} \cdot 100, \quad \sum_{n=n_1}^{n_2} G(n) > 0$	Measures the amount of building's on-site generation that is instantaneously matched by building's electricity demand	Based on measured data	Both	Csa	These indicators are applied by means of site measurements and the case study configuration is related to the electricity grid. In order to use these indicators, they may need the necessity to be appropriately adapted to the case study
	Self-sufficiency (SS)	[-]	$sc = \frac{\sum_{n=n_1}^{n_2} min(D(n),G(n))}{\sum_{n=n_1}^{n_2} D(n)} \cdot 100, \quad \sum_{n=n_1}^{n_2} D(n) > 0$	Measures the amount of building's electricity demand that is instantaneously matched by building's on-site generation				
	Net Load Profile	/	$net(n) = \begin{cases} D(n) - G(n) & first\ scenario \\ D_{mod}(n) - G(n) & second\ scenario \end{cases}$ $D_{mod}(n) = D(n) + \varepsilon_{bat} D_{bat}(n)$	Grid interaction where: - $D(n)$ is the original electricity demand profile - D_{bat} is the electricity demand profile of the integrated energy storage system - ε_{bat} is the efficiency associated to the energy storage system charge/discharge				
Heisemberg, Liu et al. 2019 [35]	Energy Flexibility factor	[-]	$F_{Flexibility} = \frac{\int_{low} q_{heating+coolign} dt - \int_{high} q_{heating+coolign} dt}{\int_{low} q_{heating+coolign} dt + \int_{high} q_{heating+coolign} dt}$	- $q_{heating+cooling}$ is the hourly energy consumption of heating and cooling. - $\int_{Low}$ is the sum of all the periods when the price is low - $\int_{High}$ is the sum of all the periods when the price is high - dt is the time step, which is one hour in the simulations	Simulation-based	Both	Dfb	Simulations were conducted in Energyplus due to its diverse functions of modelling two-pipe heating/cooling systems and achieving flexible control strategies using BMS. From the results, it has emerged that more extreme weather than prediction (colder in winter or hotter in summer) will cause lower energy flexibility.
Erba et al. 2019 [36]	Load cover factor	[-]	$\gamma_{load} = \frac{\int_{\tau_1}^{\tau_2} min[g(t) - S(t) - \zeta(t), l(t)] dt}{\int_{\tau_1}^{\tau_2} l(t) dt}$	- (t) is the energy load (use) evaluated at time (t)., - (t) the on-site generation evaluated at time (t)., - (t) the storage evaluated at time (t)., - (t) the energy losses evaluated at time (t).	Based on measured data	Both	Csa	The case study regards a passive house monitored and operated by a BACS. One of the outline of the study is that the use of

								shorter calculation time periods highlights the presence of a relatively large mismatch between the time of use and of renewable generation.
Omar et al. 2020 [37]	Cover rate	[-]	$\tau^{cov} = \frac{Q^{*EXP}}{\overline{Q}_{res}^{EXP}}$	The cover rate relates the exploited cooling energy from a specific resource to the internal heat loads through the envelope $\overline{Q}_{res}^{EXP}$	Simulation-based	Cooling	Bwh	These indicators can be easily adopted by designers and architects looking for optimal bioclimatic solutions in the early stages of building design. For ABC21, it is possible to exploit these indicators to understand the amount of energy that can be shifted considering exclusively the building fabric avoiding the systems.
	Exploitation rate	[-]	$\tau^{EXP} = \frac{Q^{*EXP}}{Q^{EXP}}$	The exploitation rate relates the exploited cooling energy from a specific resource to the environmental cooling energy that would be exploitable for that specific resource				
	Sheltering rate	[-]	$\tau^{SHE} = \frac{\hat{Q}_{sun}^{EXP} + \hat{Q}_{sky}^{EXP} + \hat{Q}_{cv}^{EXP}}{\left(\overline{Q}_{sun}^{EXP} + \overline{Q}_{sky}^{EXP} + \overline{Q}_{cv}^{EXP}\right)}$	The sheltering rate represents the capacity of the envelope to act as a barrier facing the external heat sources				
Foteinaki et al. 2020 [38]	Flexibility Indicators	[-]	$F_1 = \frac{E_{low\ load} - E_{high\ load}}{E_{low\ load} + E_{high\ load}}$ $F_2 = \frac{E_{low\ cost} - E_{high\ cost}}{E_{low\ cost} + E_{high\ cost}}$	F_1: Evaluation of total energy use during high load hours versus during low load hours F_2: Evaluation of total energy use during high production cost hours versus during low production cost hours	Simulation-based	Heating	Cfb Dfb	These indicators have been developed for a heating scenario. In order to use these indicators, they need to be adapted to the cooling scenario.
Kathirgamanathan et al. 2020 [39]	The Available Storage Capacity C_{ADR}	[Wh]	$C_{ADR} = \int_0^{I_{ADR}} (Q_{ADR} - Q_{Ref})dt$	the amount of energy that can be added to the storage system, without jeopardising comfort, in the time-frame of a DR event and subject to dynamic boundary conditions	Simulation-based	Cooling *(Case study A)*	Cfb *(Case study A)*	*(Case study A)* The simulations have been carried out for the cooling design day. The case study is characterized by a “Mass Wall” wall type based on ASHRAE Standard 90.1–2004 (U-Value of 0.857 W/m2K)] and is equipped with gas boiler for heating and two water-cooled chillers for cooling.
	The storage efficiency η_{ADR}	[-]	$\eta_{ADR} = 1 - \frac{\int_0^{\infty}(Q_{ADR} - Q_{Ref})dt}{\int_0^{I_{ADR}}(Q_{ADR} - Q_{Ref})dt}$	the fraction of the heat stored during the DR event that can be used subsequently to reduce heating or cooling power				
Lu et al. 2021 [41]	Average power deviation (ΔP)	[kW]	$\overline{\Delta P_{upward}} = \frac{\int_{t_{u0}}^{t_{u0}+\Delta t_{upward}}\left(P_{flexibility,t} - P_{reference,t}\right)dt}{\Delta t_{upward}}$ $\overline{\Delta P_{downward}} = \frac{\int_{t_{u0}}^{t_{u0}+\Delta t_{qownward}}\left(P_{reference,t} - P_{flexibility,t}\right)dt}{\Delta t_{downward}}$	The indicator ΔP (kW) provides the average power deviation during the upward (ΔP_{upward}d) or downward ($\Delta P_{downward}$) modulation period	Simulation-based	Cooling	Cfb	This study aims to assess the energy flexibility of building cooling systems using the BTM. From the perspective of building design, the parametric analysis shows that the cooling system energy flexibility is sensitive to the total structural thermal capacity, types of cooling terminals, and internal heat gains. A high thermal mass contributes to an increase of the energy flexibility regarding the peak load
	Peak power reduction percentage (γ_{peak})	[-]	$\gamma_{peak} = \frac{max\left(P_{reference,t}\right) - max\left(P_{flexible,t}\right)}{max\left(P_{reference,t}\right)}$	This indicator quantifies the peak power change rate under the energy flexibility control and reference modulation during the investigation time (24 h in this study)				
	Energy deviation (Q)	[kWh]	$Q_{valley-filling} = \Delta P_{upward} \cdot \Delta t_{upward}$ $Q_{peak-shaving} = \Delta P_{downward} \cdot \Delta t_{downward}$	The energy deviation during flexibility modulation is described using the valley-filling capacity and the peak shaving capacity				
	Energy consumption ratio (γ_{energy})	[-]	$\gamma_{energy} = \frac{\int_{t_0}^{t_0+T} P_{flexible,t}dt}{\int_{t_0}^{t_0+T} P_{preference,t}dt}$	This indicator describes the change in the total energy consumption when implementing an energy flexibility control strategy.				

								reduction during the cooling season
Tang and Wang 2021 [42]	Load covering	[-]	$F_{cv} = \frac{L_{cv}}{\int P_{load}(t)dt}$	Refers to the self-generation capability as a long-term load reduction of the energy systems in a building, which is able to satisfy part of the building load	Simulation-based	Both, focusing mainly on cooling	Cwa	The building energy performance simulation is conducted in TRNSYS, to obtain the demand baseline using the building model (Type 56) provided. The baseline simulation is conducted on a typical summer day under the indoor setting of 24 °C and 60% RH during the occupied period. The results of this study emerge that by increasing power generation and storage capacity, the energy flexibility can be enhanced. Making use of building thermal mass through the control of the HVAC system also has a great contribution to different flexibilities.
	Load shifting	[-]	$F_{sf} = \frac{L_{sf}}{\int P_{load}(t)dt}$	Is the hourly load regulation can be utilized to reshape the daily load profile of a building by smartly controlling the postponable loads and energy storage system.				
	Load shedding	[-]	$F_{sd} = \frac{L_{sd}}{P_{load}}$	Refers to the fast load curtailment within minutes of a building for a limited duration following a sudden request which mostly occurs as a contingency event in grid operation.				
	Moderate regulation	[-]	$F_{mr} = \frac{L_{mr}}{\int P_{load}(t)dt}$	Refers to load regulation in the speed of minutes.				
	Fast regulation	[-]	$F_{fr} = ave\left(\frac{L_{fr}(t)}{P_{load}(t)}\right)$	Refers to the bi-directional load regulation of buildings responding to the request of its power grid at the timescale of seconds				
Vigna et al. 2021 [46]	Flexibility Index (FI)	[-]	$FI = \frac{\int (q_{residual}^{REF} - q_{residual}^{SMART})dt}{Q_{heating}^{REF}}$ $q_{residual}^{REF} = max(0, q_{heating}^{REF} - q_{produced})$ $q_{residual}^{SMART} = max(0, q_{heating}^{SMART} - q_{produced})$	The Flexibility Index is introduced to evaluate RES efficient flexibility by adopting the forcing factor based on the availability of on-site renewable production.	Simulation-based	Heating	Cfb	These indicators have been developed for a heating scenario. In order to use these indicators, they need to be adapted to the cooling scenario.

Some indicators, as reported in Table 3, can be used only if properly adapted since the climate and/or the configurations studied (in terms of systems, devices and connection to the grid) are not in line with ABC 21. In fact, from the analysis, the influence of the climate and the configuration emerge clearly for the development of the indicators. All indicators have been verified by means of proper simulations, therefore they can be considered as a modifiable set of indicators which can be applied for the case studies of ABC 21.

4.4. Energy Flexible Building Cluster Indicators

The majority of indicators listed in Table 3 have been proposed to assess energy flexibility at the building level even if there is a growing interest to quantify this potential at the cluster of buildings level. A recent study [12] has identified a set of potential key performance indicators that could be adapted also to cluster scale, classifying them into five different categories, as shown in Table 4.

Table 4: Flexibility category reviewed

Category	Sub-category
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

4.5. Interaction with international schemes / influences

The revised Energy Performance of Buildings Directive (EPBD) promotes smart technologies and introduces the Smart Readiness Indicator (SRI) to evaluate the capability of future smart buildings to adapt their operation (using energy flexibility) to the needs of the occupants and the grid, as well as to improve their energy efficiency and overall performance.

4.5.1. Smart readiness indicator (SRI)

The SRI is an instrument for rating the smart readiness of buildings. It is based on three key 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;
(iii) the measurement of the readiness of building interaction in demand response with the energy system and the district infrastructure.

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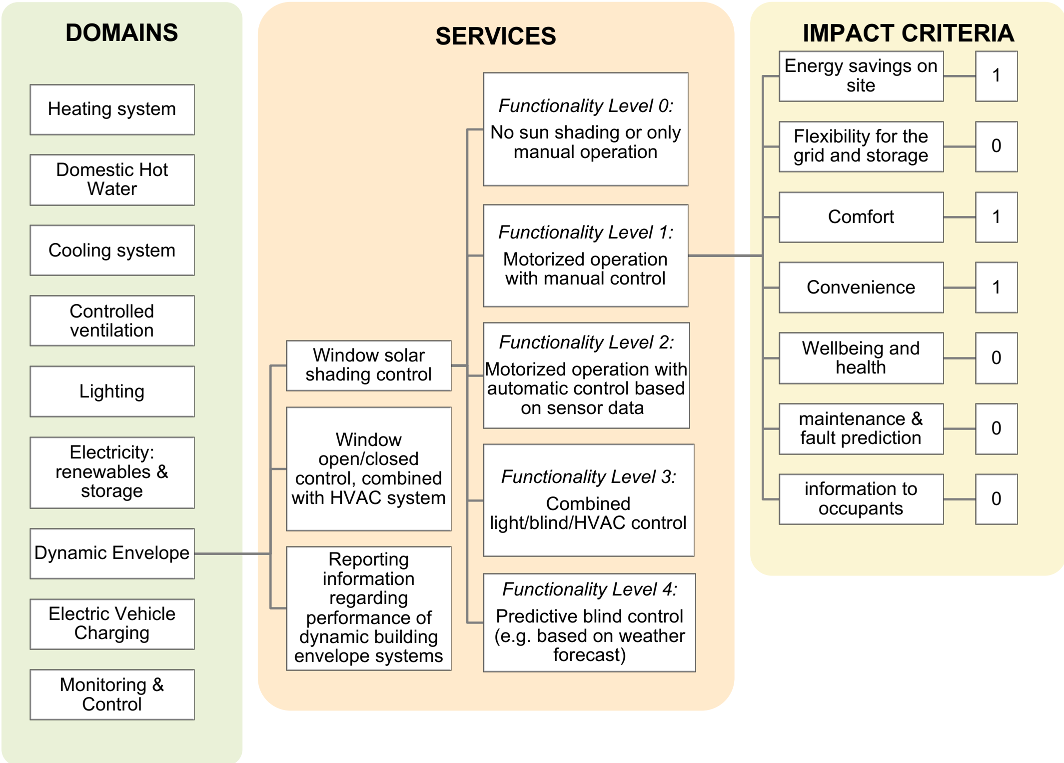

Figure 6: Structure of the SRI service catalogue.

The bottom-up approach followed to develop SRI begins with the selection of a set of reference buildings. A reference building is defined as a typical building in terms of its function, geometry, thermal quality, HVAC system and BAC system within the building stock. The analysis carried out to develop SRI have been subdivided per arguments, the ones more complaint with the current report are described below.

Energy use

In the context of the EPBD, the first key performance index is the impact of smart ready services and technologies on the energy use of buildings. The standard used for this sections are summarized in Table 5: Stardards used for the calculation of energy use

Table 5: Stardards used for the calculation of energy use

Standard	Methodology
▪ EN 52000-1:2017	For the modelling of the reference building cases
▪ EN 15232 for the energy performance of BACS ▪ EN 15500/ISO 16484-3 for electronic control equipment in the field of HVAC applications	Quantifications of the energy savings related to smart services and technologies
▪ Heating: EN 15316-1 and EN 15316-4 ▪ Hot water: EN 15316-3 ▪ Cooling: EN 15243 ▪ Ventilation: EN 15241 ▪ Lighting: EN 15193 ▪ Requirements for integrated systems: EN ISO 16484-7	Quantifications of energy use

Renewable uptake (self-production)

To quantify the measurement of self-consumption, the supply cover-factor method (γs) was chosen in accordance with the literature. This indicator can be defined as representing the percentage of on-site generation that is used directly on-site. Mathematically, it could be defined as [18]:

$$\gamma_s = \frac{\int_{t1}^{t2} min[g(t) - S(t) - \zeta(t), l(t)]dt}{\int_{t1}^{t2} [g(t) - S(t) - \zeta(t)]dt}$$

- g = the on-site generation
- S = the storage energy balance
- ζ = energy losses
- l = the system load.

Energy security (demand response)

The study carried out to develop of SRI concludes that the energy flexibility that can be afforded by a building cannot be defined by a single-value indicator since it covers diverse dimensions (time, power, energy, rebound, etc.).

SRI calculation

Finally, the smart readiness indicator is defined as follow:

$$SRS_{y,,x} = \frac{\sum_{i=1}^{n_{d,x}} F_i}{\sum_{i=1}^{n_{d,x}} Fmax_i}$$

$$SRS_x = \sum WF_{y,x} SRI_{y,x}$$

$$SRS = WF_{es} \cdot SRI_{es} + WF_{mfp} \cdot SRI_{mfp} + WF_{com} \cdot SRI_{com} + WF_{con} \cdot SRI_{con} + WF_{ic} \cdot SRI_{ic} + WF_{hw} \cdot SRI_{hw} + WF_{efs} \cdot SRI_{efs}$$

$$SRI = \frac{SRS}{SRS_{max}}$$

- SRI: Smart Readiness Indicator
- SRS: Smart Readiness Score
- SRS_{max}: Maximum Building Smart Readiness Score
- WF: weighting factors
- eg: energy savings
- mpf: maintenance and fault prediction
- com: comfort
- con: convenience
- hw: health and wellbeing
- io: information to occupants
- efs: energy flexibility and storage

5. Conclusions

Building energy flexibility is defined as the ability to manage building demand and generation according to local climate conditions, user needs, and energy network requirements.

The concept of energy flexibility originates from the approach related to demand side management but has recently received growing attention to support the growing electrification and penetration of non-dispatchable renewable energy sources. Energy flexibility is strictly related to the concepts of Smart Building and Smart Grid and research is now extending to the target of flexible energy districts.

The literature review shows a large number of indicators used to evaluate different control and operation strategies of energy flexible buildings. The choice of the indicator is case dependent and affected by the location and the configuration of the building (in terms of construction technologies, systems and interaction with the grid).

Indicators available in literature can be grouped according to three metrics:

- the quantity of energy that can be shifted
- the temporal flexibility, i.e., how long the consumption can be shifted
- the cost of utilising this flexibility.

In all these cases, the determination is based on a comparison with a reference case where no energy flexibility is exploited.

It is worth highlight that the literature analysis shows a lack of insights into indicators and example of application related to cooling dominated climates. Further, some indicators are very complex and require many input data which are difficult to be collected (especially in the absence of a proper building energy management system).

For this reason, in selected case studies and in relation to the available data, we will choose the most appropriate indicator among those analysed in Table 3, considering also that in ABC21 some buildings are equipped with a mechanical system that exploit renewable energy (passive/active storage) while others not. Further, some indicators need to be adapted to warm climates to measure e.g. the number of hours of the demand response event and the ratio among the amount of energy that can be shifted and the energy demand of a typical day.

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ANNEX A

In order to better understand the adaptability and usefulness the aforementioned quantification methods in ABC 21 (Table 2), below the classification of climates according to Koppen is reported with the aim to recognise geographically and meteorologically the identified case studies. The Koppen codes related to the flexibility case studies of Table 2 have been highlighted.

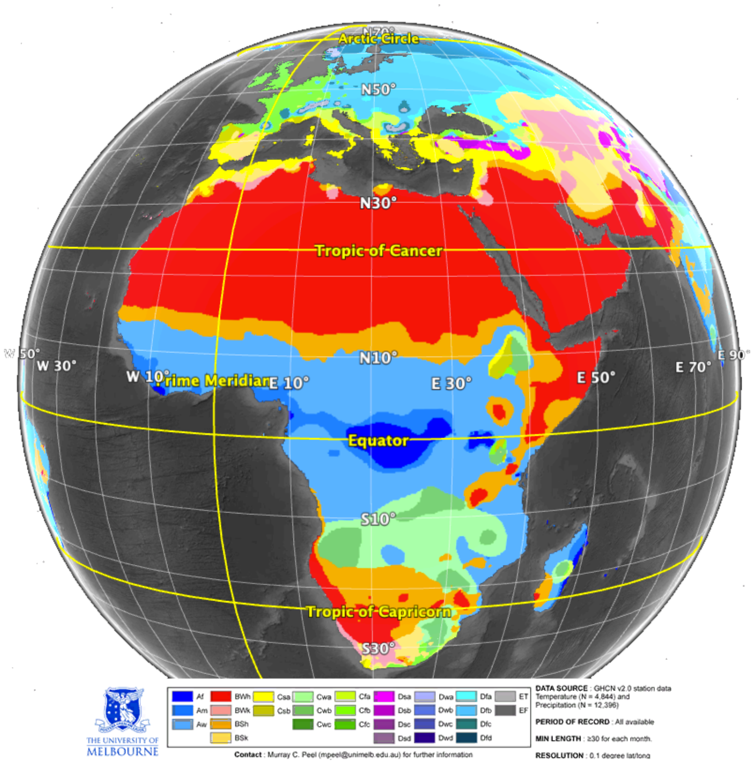

Figure 7: Africa and Europe view of Köppen climate classification

Table 6: Köppen climate classification (the items in bold are those mentioned in Table 2)

Group A: Tropical/megathermal climates	
	Af: Tropical rainforest climate
	Am: Tropical monsoon climate
	Aw: Tropical savanna climate
Group B: Dry (desert and semi-arid) climates	
	BWh: Arid desert hot climate
	BWk: Arid desert cold climate
	BSh: Semi-arid (steppe) hot climate
	BSk: Semi-arid (steppe) cold climate
Group C: Temperate/mesothermal climates	
	Csa: Temperate, dry and hot summer
	Csb: Temperate, dry and warm summer
	Csc: Temperate, dry and cold summer
	Cfa: Temperate, no dry seasons, hot summer
	Cfb: Temperate, no dry seasons, warm summer

	Cfc: Temperate, no dry seasons, cold summer
	Cwa: Temperate, dry winter, hot summer
	Cwb: Temperate, dry winter, warm summer
	Cwc: Temperate, dry winter, cold summer
Group D: Continental/microthermal climates	
	Dfa/Dwa/Dsa: Hot summer continental climates
	Dfb/Dwb/Dsb: **Warm summer continental or hemiboreal climates**
	Dfc/Dwc/Dsc: Subarctic or boreal climates
	Dfd/Dwd/Dsd: Subarctic or boreal climates with severe winters

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