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Smart sustainable buildings design principles

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ABSTRACT

The building sector is facing very serious economic, environmental, technological, and social challenges.

Sectoral approaches that usually consider individual building performance (e.g. energy, efficiency, environmental sustainability, etc.) and that they don’t consider other performances (i.e. smartness, connectivity, etc.) are not functional to ensure performance synergies, well-being and comfort for the occupants, functionality and efficiency, and the main goals of decarbonisation and sustainable development of the city. Furthermore, actual approaches don’t consider the integration and reciprocal interactions between buildings, districts and the city, in the path toward a smart, resilient and sustainable city.

The paper analyses recent indications for building sustainability in the literature, in standards, in the Union policies and in the EPBD Directives and proposes a conceptual model, a new paradigm for a holistic view, which take into account the multifaceted dimension, in terms of socio-economic, environmental aspects, energy, health, safety and security, smartness and digitization, etc, for a buildings sustainable renovation wave.

A new model is proposed for building sustainability.

KEYWORDS: *sustainable energy development, standards, system design.*

1 INTRODUCTION

The building sector is one of the largest energy consumers in the EU responsible for approximately, 40% of final energy consumptions and 36% of CO2 emissions (Eu Commission) and subsequently has a significant role in the EU’s proposal for its energy saving goal. Indicatively, an estimated 75% of the EU’s building stock (close to 30 billion m^2) is considered energy inefficient, while up to 75-85% of it will continue to be utilized in 2050 [Eu Commission https://commission.europa.eu/news/focus-energy-efficiency-buildings-2020-02-17_en].

Buildings are also facing severe challenges from an economic, environmental, technological, and social point of view, mainly constituted by climate change at a global and local level, by the increase in energy consumption due to global warming, by the vulnerability of buildings, by the need to optimize energy costs while ensuring well-being and comfort to building users.

These issues, generally, are not considered in the right way in the design phase of the building or in renovation and refurbishment actions.

So, buildings must play an active role within the context of an intelligent European energy system. Urban systems and the buildings sector are already affected by profound technological innovations, digital technologies and the energy transition are changing our cities, the way we produce and use energy, the way we construct and use buildings.

Environmental, economic and social sustainability are the primary objective that must guide the path, the 17 SDGs of the 2030 Agenda provide strategies and programs, technologies and human capital of cities can ensure a high quality of life for city users of a Smart Sustainable Resilient City.

It is not just a matter of identifying obvious climatic characterizations but of intercepting the founding characteristics of this culture: the good life and beauty of the cities, living together and the social use of public spaces, the cultural and architectural tradition.

2 METHOD

We did a cross-sectional study of European Union documents and legislative measures about buildings performances, scientific research outcomes, technical standards development based on the knowledge resources offered by applied scientific research to identify the deriving optimal approach to smart sustainable building design today.

3 THE REFERENCE FRAMEWORK

3.1 European policies context

EU have been developing policies and measures to generally reduce the actual energy use in buildings, focused on energy efficiency topic.

The European Union is committed to the United Nations 2030 Agenda with its 17 Sustainable Development Goals (SDGs) and the 2015 Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC).

The European Union has outlined in the Green Deal a strategy based for the complete decarbonisation of economy and of the energy systems, with the pursuit of climate neutrality by 2050.

The Green Deal recognises energy system as one of the strategic sectors in driving the sustainable development of countries

Buildings are the main responsible for GHC emissions and as a key to achieve the 2030 and 2050 climate goals.

The European new energy market, fully integrated, interconnected, and digitised, with the diffusion of new digital technologies, smart grids, and demand response mechanisms, energy communities, allow an effective energy transition and the participation of citizens as prosumers.

3.2 Scientific research on building’s sustainability

A holistic approach to building’s sustainability should be implemented in the EU, which should consider optimising buildings’ performances and associated costs.

Scientific research and standardization works are now oriented to a new holistic concept of building sustainability (Sustainable Cities and Society, ScienceDirect, Sustainable Cities and Society Journal, “Clarifying the new interpretations of the concept of sustainable building”, Umberto Berardi, 2013), CEN/TC 350 - Sustainability of construction works standards.

Summarizing the recent interpretations in literature, a sustainable building can be defined as a healthy facility designed and built in a cradle-to-grave resource-efficient manner, using ecological principles, social equity, and life-cycle quality value, and which promotes a sense of sustainable community”.

According to this, a sustainable building should increase:

• demand for safe building, flexibility, market and economic value,
• neutralization of environmental impacts by including its context and its regeneration,
• human wellbeing, occupants’ satisfaction and stakeholders’ rights,
• social equity, aesthetics improvements, and preservation of cultural values” (Berardi, 2013).

3.3 The standardisations activities

International and European standards on sustainability in buildings suggest how buildings can contribute to the social, economic, and environmental aspects of sustainability.

The framework developed by the standard ISO 21931-1:2010 “Sustainability in building construction – Framework for methods of assessment of the environmental performance of construction works – Part 1: Buildings” identifies and describes the aspects to be taken into consideration to develop and apply the methods for the evaluation of the environmental performance of new and existing buildings. These evaluations serve to compare performance and monitor progress towards improvement and sustainable development.

ISO standards have been implemented as UNI EN ISO 14020:2023, relating to environmental labelling, UNI EN ISO 14040:2021, on life cycle analysis and UNI ISO 15392:2019, on the general principles of sustainable development in construction.

At European standardization level, references must be made to the standards of the CEN/TC 350 "Sustainability of construction works" committee.

The European standards EN 15978:2011, EN 16309:2014, EN 16627:2015, EN 15643:2021 define environmental, social, economic performances that should accompany technical and functional performances in a building (fig.1).

Fig.1: Building integrated performances

Standards promote a holistic approach, that considers, in an integrated and interrelated way, all building performance, environmental, social and economic performance, as well as technical and functional performance.

Sustainable buildings are those that contribute to the goals of the 2030 Agenda.

3.4 Smart sustainable building definitions

Various definitions have been proposed for these buildings by various groups, scientific literature, polytechnics, commercial entities and various organizations that have evolved over the last years.

The definitions are useful for designers to understand the elements of the architecture of a smart building and to indicate the design elements characterizing it.

In literature the intelligence embedded into intelligent building are claimed to enable them to be highly responsive to users' needs, the environment, and the society, and to be effective, in minimizing the environmental impacts and natural resource wastes (Kua and Lee 2002; Ghaffarian Hoseini 2012).

Reduction of operational costs through efficiency in energy management and the capability of being "user oriented" encompassing improved safety, health, and well-being are other important goals of IBs (Silva et al. 2012; Cempel and Mikulik 2013).

From the above review, it can be concluded that existing definitions can be categorized into three clusters, namely: performance-based, system-based, and service-based definitions.

At the international level, the International Electrotechnical Committee's (IEC) ITU-T Y.4550-series – "Smart sustainable cities" standard bases the paradigm of "smart buildings" on the ability of individual systems within buildings to communicate, integrate and function in such a way as to allow numerous and complex controls to generate a much-improved response to needs, many types of stimuli and a reduced overall environmental impact.

The ISO standard ISO/TC268 37173:2023 "Smart community infrastructure- Guidance for the development of smart building information systems" fits into this scenario, contains a complete definition of Smart Building: "an intelligent building capable of identifying and adapting to expected and unforeseen changes through the effective use of data, information and communication technologies and that continuously improves the forecasts and actions in response to the various needs of building values, urban activities and urban operations".

In this way, the forecasting aspect, responsiveness and interaction of the building with the urban environment are confirmed.

At European level in directive (EU) 2018/844 the Smart Readiness Indicator (SRI), an indicator of the capacity of the building to manage and optimize itself and to interact with occupants and the grid, is defined.

The "smartness" concept of the building is defined as the technical capability of: (a) managing itself efficiently (b) being able to interact with and respond to its occupants (c) being able to actively and passively interact with the grid.

Directive 2024/1275 EU indicates four key functionalities:

a) the ability to maintain energy performance and operation of the building through the adaptation of energy consumption for example through use of energy from renewable sources.

b) the ability to adapt its operation mode in response to the needs of the occupant while paying due attention to the availability of user-friendliness, maintaining healthy indoor climate conditions and the ability to report on energy use.

c) the flexibility of a building's overall energy demand, including its ability to enable participation in active and passive as well as implicit and explicit demand response, through its energy storage and release of energy back to the grid, for example through flexibility and load shifting capacities.

d) *the ability to improve its energy efficiency and overall performance using energy-saving technologies.*

The study commissioned by European Commission provide an assessment methodology for calculating and measuring the SRI, the delegated regulated (EU) 2020/2156 of 14 October 2020 and the delegated regulated (EU) 2020/2155 of 14 October 2020, represent the legal assessment methodology for calculating SRI.

At Italian level the Italian Electrotechnical Committee (C.E.I.) has published the "Smart Building White Paper", the first guide issued by a standardization committee, which provides extensive documentation, both at the regulatory level and from an architectural point of view [1].

Finally international protocols as WiredScore or Smartscore, highlight between the key elements of smart buildings, the presence of digital and smart technologies and connectivity in the integrated design of a building and communicate to the market its characteristics of intelligence.

3.5. The holistic concept of building's sustainability

European directives and strategies deal with energy efficiency (Energy Performance Directives), nature (EU biodiversity strategy, forest strategy, climate law), circularity (Circularity Action Plan), decarbonization (Climate Target Plan 2030) and new energy market (Directives 944/2019, Directive 2018/2001), whole life carbon (Level(s) protocol), architectural beauty,(New European Bauhaus), digitalization (smart readiness indicator SRI -Directive 844/2018, Digital Compass), smart cities and climate neutrality (100 climate neutral and smart cities initiative), resilience (Major Adapt initiative).

From Directive 2002/91/EC of 16 December 2002 and Directive 2010/31/EU of 19 May 2010, focused mainly on energy efficiency, there has been a progressive transition to the consideration of other further building performances.

EPBD 3 already provides a "whole building" approach by promoting the improvement of the energy performance (i.e. energy efficiency and renewable energy use) of buildings, considering both outdoor climatic and indoor climate requirements and cost-effectiveness.

Lastly the "A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives"- COM (2020) 662 final" contains the key principles for building renovation which summarize the entire conceptual path of the EU policies on buildings: energy efficiency, decarbonisation, integration of renewables, life cycle thinking and circularity, health and comfort, aesthetics and architectural quality.

We can note that in European policies there are no may indications for building resilience to climate changes, the Major Adapt initiative is regarding more urban resilience.

So, in a smart sustainable building we can find all the above-mentioned performances.

Level(s) protocol is a common European system of sustainability metrics and labels to classify buildings for their combined energy, IEQ, comfort and wellbeing, structural, fire safety, and sustainability performance, accompanied by a building passport that testifies to the history of its entire life cycle.

At the same time is it is expected a revision of EPC, energy performance certificates, to consider other building performance in addition to energy efficiency.

A holistic approach that considers all the building's performances and similarly a system for measuring performance and communicating with users is recommended [2], [3].

4 PROPOSED APPROACHES

In consideration of the summentioned context the authors have the opinion that sectoral, silos approach that consider individual building performance and that don’t consider reciprocal interactions, synergy and integrations between performances, interlinked and interacting factors is not functional to a new sustainable building approach.

Therefore, a new multidimensional approach to buildings’ sustainability is outlined (fig.2).

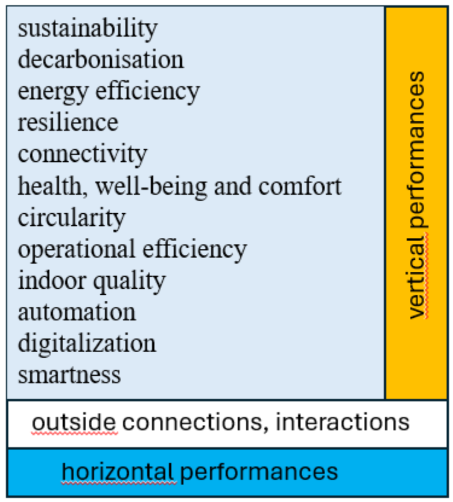

Fig.2: Vertical and horizontal building performances considered in the study

“Vertical performances” represent the multidisciplinary functional and technical performances that concern the building, they include environmental sustainability, decarbonisation, energy efficiency, resilience, connectivity, health, well-being, comfort, circularity, operational efficiency, maintainability, indoor quality, durability, building safety and security automation, digitalisation, and smartness.

Sustainable buildings are interrelated to the whole city by physical, social, economic, and environmental connections, this shows the importance of the cross-scale relationships between a building and its surroundings, together with the ever-changing flows between them and the cross-scale evaluations of sustainability.

” Horizontal performances” represent the connections of the building, as part of the urban energy system, with other buildings in neighbourhoods (positive energy districts, with energy communities, and with the city, connections that allow the exchange of energy, data, and services from the building to these other entities between smart energy and ICT networks.

Sustainable building is “a building that fulfils all three economic, environmental and social dimensions as well as technical and functional requirements, based on its intended use, during the life cycle of the building” (EN 17680:2023).

Buildings that ensure all vertical and horizontal performances contribute to the sustainable development of city.

This approach is just reported in the standard drafted by UNI/TC 058 “Sustainable cities, communities and infrastructures” titled “Sustainable cities, communities and infrastructures - Integration and interconnection of buildings-methodological reference model”- prUNI1610383, in public inquiry.

4.1 Smart sustainable building new concept

Smart sustainable buildings are the drivers for the transformation of our current fossil fuel-dependent energy system into an energy-efficient smart urban energy system. a distributed, decarbonized (renewable sources), digitized and demand-side flexible generation system, they can tackle the twin challenges of the green and digital transitions.

The concept of "smart buildings" has been around for several years and is mainly based on the ability of internal systems to communicate between them, with the occupant and with the grid,, to provide a much-improved system both in terms of energy and operational efficiency and comfort for occupants.

Today a smart building can maximize energy efficiency and optimize energy consumptions, optimize operational efficiency through cost-effective management of the assets in the building, integrate building equipments and sub-systems and optimize the use of spaces.

A smart building,can be considered as a hub of services, the “building as a service” concept (fig.3):

- energy services: management of energy consumption and operation even remotely, real-time monitoring, storage and tracking of consumption trends through dashboards, predictive analysis of energy consumption and production, energy efficiency services also through aggregation, access to the smart grid, management of renewable energy production and storage systems, access to price signals and the possibility of load shifting by providing flexibility to the network.
- building management services: optimization of operating costs, communication services for the common areas of the building, predictive management of maintenance and fault detection, management of systems and automation systems to ensure increasingly personalized comfort, well-being and health, real-time management of the building's shared resources, open space, rooms for common services (conferences, co-working spaces, recreational areas, etc.), parking facilities, EV smart charging.
- services to the person: safety, comfort and well-being, telemedicine, digital services of the PA, communication services for private spaces, geolocation, signalling and guidance services, etc.

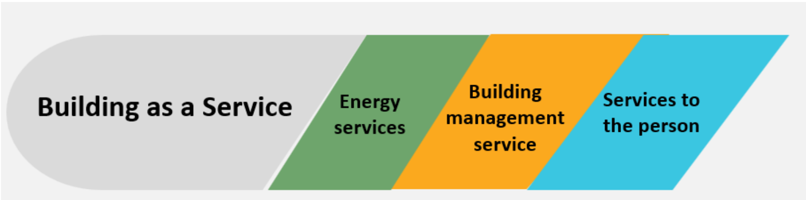

Fig. 3: Building as a service concept

The use of smart and I.C.T. cutting-edge technologies, IoT, cloud computing, edge computing, big data, which provide real-time data from sensors to adjust settings based on occupancy, weather conditions, and energy consumption patterns [4], advanced building management systems (BMS) that integrate various subsystems and devices into a centralized platform for centralized monitoring, control, and analysis of building operations, lead to improve operational efficiency, predictive maintenance, and proactive decision making, energy efficiency and enhanced occupant comfort [4],[5].

The Building Energy Management Systems (BEMS) can integrate a BMS, this integration enhances the traditional control functions of a BMS with the advanced energy monitoring, optimization, and fault detection capabilities of a BEMS, leading to improved energy efficiency and system health.

A smart building is equipped with an information system that can realize forecasting, exchanging and sharing data with the Smart City (as its energy consumptions), accesses to smart building subsystems and sensors and enables rapid deployment of preferential applications and services. In addition, the system can interconnect cloud services or building edge computing.

Building digital twin technology allow predictivity and real time management

Intelligence in a building thus refers to the use of technologies to collect and process the available data to make the appropriate decision to achieve the highest energy efficiency and about building management, to optimize the individual's comfort and energy use based on the current data, the history and evolution of power consumption and the prediction of its immediate evolution.

Artificial intelligence and machine learning techniques provide smart buildings with the ability to better understand the overall energy consumption of equipment, the environmental external parameter evolution throughout the day, the appliances usage, learning from the performance history can make decisions in real-time and predict energy use to achieve the highest energy use efficiency.

Finally building resilience is a property to prevent and minimize damages and restore building functioning after a harmful event.

5 THE INTERACTIONS WITH USERS, THE GRID, THE BUILDINGS, THE CITY

The smart energy system could be figurate as:

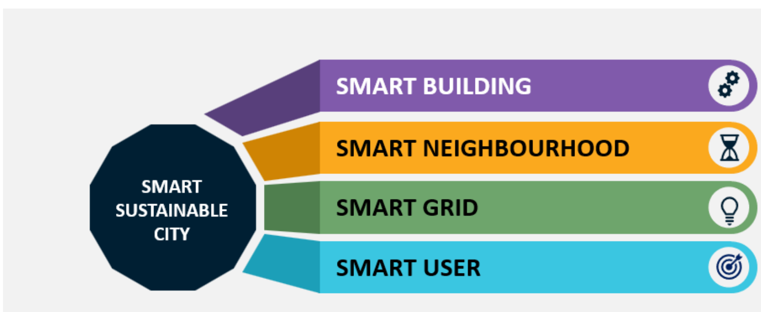

Fig.4: Smart energy system elements

Smart buildings, smart district, smart grids and smart users are the elements of this system (fig.4).

Users should have a virtuous behaviour in managing the building systems, an active role in interaction with the systems and the grid, optimizing energy consumptions and needs.

A smart building interacts with users, with the grid, with other buildings, with the neighbourhood and the whole city.

5.1 User interactions

Any smart building will have to allow you to explore and design the general feeling (in terms of acceptance, comfort, well-being, etc.) of the occupants, increase the knowledge and understanding of the desires, expectations, behaviours and uncertainties of the end users.

Different end-user profiles require different solutions and trigger different reactions and behaviours (early users vs. change-averse people).

To ensure maximum attractiveness and acceptance by end-users, the smart building should:

- provide end-users with easy-to-obtain and acquire information on how to use the building;
- provide monitoring feedback to end-users, i.e. personalized information about how the building operates, Feedback includes energy consumption, indoor environment quality, health-related parameters, household appliance usage data, etc. Information can be provided through simple data monitoring visualization, analysis of historical trends, specific widgets, or ad hoc suggestions;
- enable the above-mentioned exchanges of information with the end-user through simple and user-friendly interfaces;
- provide recommendations to users and facility managers to improve building operations or based on their preferences (energy savings, comfort, air quality), e.g. providing advice on opening windows and/or moving blinds/curtains to improve the thermal environment.
- dynamically adapt the operation of the building to the preferences and behaviours of the end user, this means that they both learn from the end-user's behaviours and act accordingly on the building's equipment.

5.2 Grid interactions

Relations with electric grid are characterized by the purchase of energy or the introduction of excess self-produced energy with a phase shift between the time of production and consumption.

To actively interact with the network, buildings are shifting from consumers to producers, which has led to the terminology of the prosumer (producer + consumer). Using buildings to produce energy by integrating renewable energy systems is one of the key principles of our transforming energy system. Another key aspect is to use the storage capacity of buildings to move loads over time [5].

For the active interaction of a building with the smart grid, the potential for temporal flexibility of a building regarding its characteristics related to energy consumption, energy production or both, the ability of the building to take energy from the grid, store it for a certain period of time and send it back to the grid is essential.

Smart grid integration consists also in the ability to shift energy demand according to grid needs or the ability to fully participate in smart grid solutions.

Energy flexibility, demand response allows an active participation of user in energy market through user's aggregators, smart metering devices measure and collect energy data.

5.3 Interaction with buildings and the city-neighbourhood approach

Smart buildings allow interaction with other buildings, building blocks, neighbourhoods, energy communities and with the city management platform, through the exchange of data and information flows and energy flows and allow an effective management of the neighbourhood energy system and of the energy communities energy systems (fig.5).

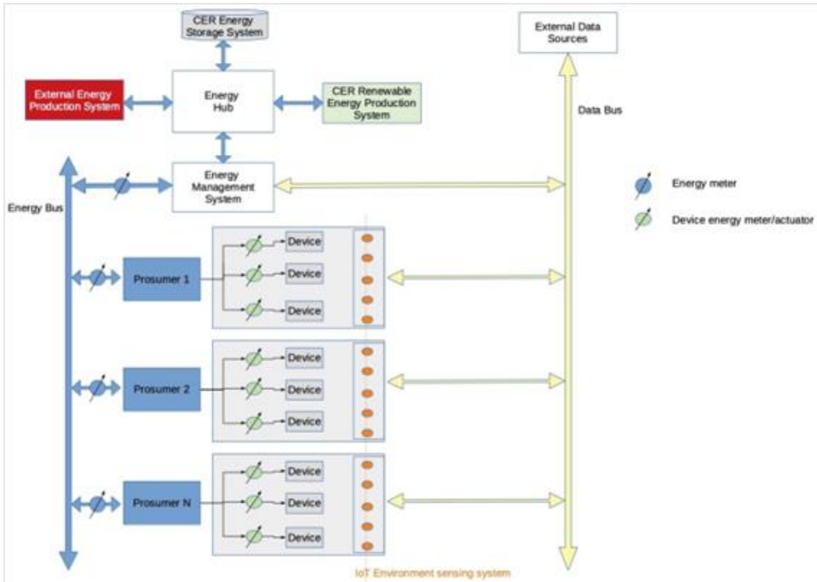

Fig. 5 A simplified general block diagram of a CER

The main components are the energy hub, the energy management system and the prosumers, together with the IoT sensing system able to collect data from each prosumer and closing the control loop using the data bus to the Energy Management System.

The Energy Management System is the core of the complete CER, whose aim is to optimize the energy usage/storage/delivery to the connected prosumer depending on the information acquired from the network and from the IoT sensing system deployed to monitor the prosumers needs.

In this phase, also information acquired from the CER History Database, taking care of the habits of each prosumer, information about the energy production forecast can be also inferred to correct the energy management policy in real time.

Together with the efficient energy delivery to each prosumer, the Energy Management need to take care of the energy usage delivered to each prosumer to compute the costs for each.

The problem is not trivial, as t needs to observe huge quantities of data of different kind to optimize the energy use. This task can be carried out efficiently with the recourse to Artificial Intelligence, setting up enough Machine Learning algorithms to address jointly the general problem.

Successful decarbonisation of the EU building stock calls for an integrated, participatory and neighbourhood-based approach.

The neighbourhood/district approach is recognised in the 2024 EPBD recast as a cost-efficient way to scale up renovations while considering social and environmental aspects.

In scientific literature [6],[7],[8],[9],[10],[11],[12],[13],[14] has been discussed the importance to go beyond the sustainability assessment of single buildings and to enlarge the assessment scale to energy communities to meet all the different aspects of sustainability.

Neighbourhood/district approach has the potential to lead to optimal solutions at the local level, combining energy efficiency, renewable energy production and flexibility with other benefits and ensuring the consistent sustainable development of cities and territories.

6 PROPOSED DESIGN PRINCIPLES

Current buildings design is based on standard models of behaviour and needs of the occupants, the use of simple systems of control of the systems allows them to adapt their functioning according to the external and internal conditions.

The summentioned analysed buildings performance and the interactions and connections with the outside lead to a smart sustainable building new concept design.

It can be considered as a system in which various sub-systems, technological as equipments, automation and control systems, IoT sensors, communication infrastructures, and natural as nature-based solutions, coexist in an integrated way to offer new functionalities and personalized services to occupants, comfort and well-being, new services related to the smart grid.

Smart building architecture, functional to these objectives, is based on:

- equipments, systems and solutions;
- automation and control systems;
- IoT sensors and devices, enable the continuous measurement and monitoring of crucial parameters such as lighting, air quality and temperature.
- the network infrastructure;
- the management and control platforms.

In a smart building, all the equipments, (i.e. electric, RES and storage, HVAC, electric charging, and systems as safety and security people detection, BACS, spaces reservations, monitoring), can be managed in an integrated, intelligent and automated way, through the adoption of a supervision and control infrastructure.

The integrated and holistic approach to build new smart sustainable buildings or to transform existing buildings is based on the following principles:

- reduction of energy demand, by bioclimatic technics, solar reflective materials, occupant aware behaviour;.
- connection with nature, nature-based solutions for reduce energy demand and increase building resilience to face and mitigate the effects of climate emergency, green roofs, cool roofs; green façade;
- efficient use of resources and materials, circularity and whole life carbon approach;
- the use of high energy efficiency solutions, passive and active;
- careful design of building envelopes to improve energy efficiency and shading systems;
- the "smartization" of electrical, electronic systems with the implementation of data collection, command, control, measurement, monitoring and management, interaction functions;
- use of renewable energy sources for decarbonization, that also allow users to take an active role in the electricity market and to participate in the energy communities;
- automation and control monitoring systems for equipments;

- use of digital and ICT technologies for communication infrastructure for connectivity, open protocols for communication and data collection;
- control and management platforms, for real-time energy monitoring, collecting, processing and analysis of acquired data, prediction of consumption, operation and conditions of use [5].

Sensors, smart and IoT devices and functions to communicate and interact with each other are managed, controlled and automated in a remote way by a Building Management System (B.M.S.).

BMS contribute to the optimisation of the building functioning and control any device from passive architectural elements, such as shading or opening elements, to active systems such as heating, cooling, ventilation, and lighting systems.

Using BMS with distributed energy resources (DERs) reduce energy costs and overall CO_2 emissions and provide flexibility services in the electricity energy market.

6.1 Communication infrastructures

A Smart Building can become the piece of a more complex system of a higher order, such as a Positive Energy District (PED), a Smart City or an Energy Community or provide information to a Smart Grid (e.g. to reduce energy peaks, the analysis of Key Performance Indicators, etc.).

Buildings need to be equipped with communication infrastructure to exchange information and collaborate with other stakeholders in the city on a more abstract level, it represents the building's ability to connect to other IT systems.

Connectivity is the nervous system of the building and encompasses the data network that connects all sensors and actuators to react with the environment.

The widespread ultra-fast broadband connectivity of buildings makes it possible to take advantage of services and applications via the web, to send and receive data and information also through Internet of Things (IoT) technologies, to building sensors to communicate incessantly with each other, to integrate a machine learning platform with IoT sensors and/or with 5G technologies, in an automated way.

Connectivity networks allow building data to be sent to external applications and services with open APIs, which allow a horizontal and vertical data exchange that is perfectly scalable and adaptable to any load-bearing infrastructure, physical or radio. It is suggested that these APIs be based on the REST API architecture. A fundamental reference, at the italian level, are the "Guidelines Technologies and standards for the security of interoperability through APIs of IT systems" of AGID. Open standards, such as the TCP/IP protocol, are recommended for better software integration for system interoperability.

7 FUTURE DEVELOPMENT

The smart building evolves towards the "smart-cognitive building" building model, by the integration of an AI machine learning platform with IoT sensors, edge computing, 5G technology, and building modelling using digital twins (through the virtual simulation of building spaces and objects through interactive 3D digital reconstructions).

Smart cognitive building can analyse in detail the actual use of the premises and modelling the behaviour of patrons through artificial intelligence to obtain predictivity, energy efficiency, operational efficiency and occupant satisfaction, customizing the environments according to the individual needs of those who work there.

These buildings have the ability to learn based on the information captured in real time by the numerous IoT sensors and edge devices, scattered inside them and also in the structural elements, data that are understood and analysed by machine learning platforms, and are able to offer performance that is increasingly in line with the needs of users, as an organism capable of learning adaptively from the surrounding environment and self-organizing itself in plant functionality [15].

Artificial Intelligence is revolutionizing smart buildings design, offering advanced solutions for energy management, optimization, and integration in neighbourhoods or energy communities. By harnessing the power of AI, smart buildings can achieve greater efficiency, reliability, and sustainability, while also providing economic and social benefits to the community.

The successful implementation of AI requires a holistic approach, encompassing infrastructure development, micro-grid management, data management, and community engagement [16].

Some applications are:

1. AI-driven energy management:
    - predictive analytics:
        - ✓ demand forecasting: AI algorithms analyse historical energy consumption data and external factors like weather patterns to accurately predict future energy demand for planning and optimizing energy generation and storage in building,
        - ✓ renewable generation forecasting: AI models predict the output of renewable energy sources (RES), based on weather forecasts and historical data, improving the integration of renewables into the building supplies.
    - load balancing and optimization:
        - ✓ dynamic load management: AI systems dynamically adjust energy distribution based on real-time demand and supply conditions, ensuring efficient load balancing and preventing grid overloads.
        - ✓ energy storage optimization: AI optimizes the charging and discharging cycles of energy storage systems, to use stored energy efficiently and effectively.
    - micro-grid management:
        - ✓ grid stability: AI monitors grid conditions in real-time and autonomously adjusts the flow of electricity to maintain stability, important with the intermittent nature of RES,
        - ✓ fault detection and response: AI detects anomalies and potential faults in the grid, enabling rapid response to prevent outages and reduce downtime.
2. Enhancing renewable energy utilization:
    - integration of distributed energy resources (DERs):
        - ✓ coordination of DERs: AI manages the operation of distributed energy resources like solar panels, wind turbines, and battery storage, ensuring they work in harmony to meet the community's energy needs,
        - ✓ virtual power plants: AI aggregates multiple small-scale energy resources into a single virtual power plant, optimizing their collective output and making them more effective in stabilizing the grid.
    - energy efficiency improvements:

- ✓ smart thermostats and appliances: AI-enabled devices learn usage patterns and adjust settings to optimize energy use, reducing consumption and lowering energy bills.
- ✓ building energy management: AI systems control heating, ventilation, and air conditioning (HVAC) systems, lighting, and other building systems to maximize energy efficiency and occupant comfort.

3. Economic and social benefits:
   - cost reduction:
     - ✓ operational cost savings: AI automates routine tasks and optimizes energy use, leading to significant reductions in operational costs for buildings,
     - ✓ energy savings: by improving the efficiency of energy use and reducing waste, AI helps buildings owners save on energy costs.
   - social equity and inclusion:
     - ✓ access to affordable energy,
     - ✓ AI-driven systems can help manage and reduce energy costs, making RES more affordable for low-income households,
     - ✓ community engagement: AI tools facilitate better communication and engagement with community members, providing them with insights and control over their energy use.

8 CONCLUSIONS

Smart Building is an efficient ontology for building design and management, but sustainable buildings is more effective and responding to city sustainability goals.

This study analyses the whole context for smart sustainable buildings concept and, with a scalable approach, the elements and interactions of the smart sustainable ecosystem in the city.

We demonstrate, with research, references, and exploration of practical implementations, what we should consider as significant component of future smart sustainable built environments.

A holistic approach and a new sustainable buildings concept design are proposed to satisfy environmental, social and economic targets and to face cities challenges, with a user centric approach, to contribute to sustainability pillars.

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