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Understanding smart sustainable buildings nexus to the new smart energy system

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Abstract: Decarbonization, well-being, and high quality of life for citizens are some of the targets of the 17 Sustainable Development Goals of UN Agenda 2030. In this context, smart and sustainable cities should adopt cutting-edge technologies with the least environmental impact and an energy-efficient use for constructing infrastructures. Smart and sustainable buildings that maximize performance and energy use at all stages of the building life cycle are paramount. Smart, sustainable buildings are the key elements of positive energy districts and a smart, resilient, sustainable city. In this paper, after a cross-sectional summary of the European Union documents and legislative measures about building performance, the scenario on the main and appropriate methodological steps for identifying the optimal elements of positive energy districts is underlined.

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1. INTRODUCTION

The European Green Deal and global net-zero initiatives at global level and at European level (EU Mission 100 climate-neutral and smart cities) need a deep change both in the way energy is produced/used and in the way buildings are constructed and employed. The twin green-digital transition will transform urban energy systems through the decarbonization, decentralization, digitalization, and electrification pillars. Buildings, neighborhoods, and districts are elements of the new smart energy system if they are transformed taking care of such pillars.

The fully integrated, interconnected, and digitized European new energy market provides several opportunities with the diffusion of novel digital technologies such as smart grids, energy communities, and demand-response mechanisms. Technological progress has been accompanied by the active participation of consumers who have a skill in managing demand side. The decentralization of the electricity market and its transformation in a consumer-centric structure are the goals to achieve. Decentralization improves energy resilience and reliability and reduces energy losses because new short-distance and reliable energy infrastructures are developed. This consumer-based model leads to the phenomena of energy democratization as consumers can become producers Moretti and Stamponi [2023]. Prosumer is the name assigned to a generic active consumer which can be a private individual, household, organization, community, school, hospital, and so on Parra-Domínguez et al. [2023].

Highly energy efficient, sustainable, digitalized, flexible and smart buildings have the characteristics to allow this change of paradigm. Positive Energy Buildings (PEBs) and Net-Zero Energy Buildings (NZEBs) are some of the new concepts introduced for defining building characterized by equal or more energy generation to usage, an equal to net-zero energy cost and zero carbon emission Sartori et al. [2012], Mousavi et al. [2023].

To improve the energy performance of buildings, the EU has established a legislative framework that includes the revised Energy Performance of Buildings Directive (EU/2024/1275) and the revised Energy Efficiency Directive (EU/2023/1791) 26 [2020]. Many strategies can be adopted to meet the NZEB requirement aimed at either a reduced building energy demand by means of efficient design techniques/more conscentious behaviour or a raised renewable energy generation.It is therefore evident that NZEB designs have to take into account available infrastructures, available energy sources, climate and economic factors Wu and Skye [2021].

In this paper a description of the major components to be addressed to obtain a holistic approach for smart and sustainable building design is proposed.

The paper content is not intended to give a complete and exhaustive methodology for designing sustainable buildings, instead proposes and highlights the needs and the reference of the regulations to be addressed in the design of smart buildings.

2. RELATED LITERATURE

The growing interest in smart buildings, as well as the technological innovation in this field, were the driving forces behind the development of several studies for the

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implementation of various applications such as energy and building management, alarm management, personal safety, intrusion event management, and so on [Yuekuan Zhou [2024]].

In fact, smart buildings are able to draw out welcome shifts, for example, resilience, sustainability, connectedness, and smart environments for people's daily life [Apanavi [2023]].

Energy, mobility, well-being, security, water, and waste are the key technological applications for the shift toward smart buildings [Domingos and Ferreira [2024], Baharetha [2024]].

Several challenges and obstacles need to be overcome to this day for the adoption of advanced technologies in smart buildings to create an energy-efficient, comfortable, and safe environment for its occupants [Baharetha [2024], Affonso [2024]].

The great disparities in building components, the large amount of data to acquire and deal with, and the difference in building dynamics make the design of real-time building management systems hard. Several control systems have been indicated in literature in the past ten years which adopt model-based control approaches for balancing occupant comfort and energy-saving factors [Ruusu [2019], Biyik [2019]].

The modeling of the process for this type of approach requires a mathematical representation of building dynamics, which is very challenging because buildings are generally large-scale systems with a high degree of uncertainty. To overcome this obstacle, learning-based building management systems could be used based on artificial intelligence and machine learning techniques [Ming [2020], Megahed [2019]].

In the last five years, some studies have been conducted on combining machine learning with model-based control techniques for buildings management to merge the advantages of the two approaches [Karg and Lucia [2018], Reynolds [2018]]. Such hybrid approaches complete and extend the possibilities in developing smart buildings.

3. SMART BUILDINGS AND SMART SUSTAINABLE BUILDINGS

The concept of sustainability is related to people quality of life improvement which implies social, economic, and environmental condition enhancement. The built environment is highly relevant in everyday life and represents a key factor for both energy demand and greenhouse gas emissions. Natural resources, ecosystems, and the public are the primary areas where the building sector causes environmental impact. Therefore, sustainable buildings are decisive for the transition to a sustainable environment. Sustainable building, often called green building, is defined as "the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building life-cycle from siting to design, construction, operation, maintenance, renovation, and demolition" [Olabi et al. [2025]].

The reduction of resource consumption, the re-using and recycling of resources, the removal of polluting/dangerous substances and the environment protection are some of the fundamentals of the sustainable building philosophy [Jaradat et al. [2024]]. Also, the site planning and design are a great problem in the sustainable building framework, as it makes the creation of a feasible location possible .

Energy efficiency is considered a key element in moving towards sustainable buildings. In this context, PEBs and NZEBs are particularly relevant. According to the PEB idea, an energy system efficient, flexible and with optimal production is necessary. In particular Mousavi et al. [2023]:

- innovative technologies able to lower energy demand are necessary to meet the efficiency requirement;
- a balanced management of energy demand and supply is required for the flexibility necessity;
- cheap and clean energy sources garantee an optimal production.

Among the key technologies for NZEBs, Intelligent and smart technologies are emerging for home energy management such as Internet of Things (IoTs), data analytics, digital twin, Building Information Modeling (BIM), Building Management Energy System (BEMS), 5G and Artificial Intelligence (AI) [Ohene et al. [2022]].

Smart Building is defined by the International Organization for Standardization (ISO) standard 37173:2023 "Smart community infrastructure- Guidance for the development of smart building information systems" as "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", with particular attention to urban activities and operations". Thus, a smart sustainable building is focused on improving the quality of life of users, forecasting and providing user needs related to urban activities and services. Smart building provides efficient solutions for energy consumption reduction, environmental impact decrease and renewable energy resource use [Pasquale Capezzuto [November, 21, 2024]].

Smart Buildings are key parts of a smart city, which is an urban environment that uses smart technologies and data analysis to optimize city functions [Silva et al. [2018]]. Smart city is the basis for sustainable development because it creates effective solutions that look to energy management, transport, healthcare and governance so as to ensure a better quality of life for citizens [Chen et al. [2022]].

4. SMART SUSTAINABLE BUILDING INTERACTIONS

A smart building interacts with users, the grid, other buildings, the neighborhood, and the whole city, according to the smart sustainable city paradigm. The directive (EU) 2018/844 [jpi urbaneurope.eu/ [2024]] and the directive (EU) 2024/1275 introduce the smart readiness indicator (SRI) EU scheme, which has been experimented with in several European countries.

The EU Smart Readiness Indicator (SRI) is an assessment method for the evaluation of building ability to

use information technologies and advanced electrical systems, as stated in the 2020/2155 and 2020/2156 Delegate Regulations. This merit figure aims to make it easier to obtain smart buildings regarding both energy consumption/storage and a comfortable/healthy environment for users. The SRI evaluates the smart readiness of buildings in their capacity to perform three functionalities:

- to optimize energy efficiency and overall in-use performance;
- to adapt their operation to the needs of the occupant;
- to adapt to signals from the grid.

User interactions Smart, sustainable buildings represent the concept of holistic sustainability because they provide social, economic, and environmental sustainability. Users/citizens have a behavior that emphasizes well-being, equity, and individual empowerment. Moreover, they consider both long-term impacts produced by the conceived economic solutions and take actions to guarantee the protection and restoration of the natural environment. For example, users/citizens learn virtuous behaviours in managing energy, use smart appliances and efficient equipments (i.e. heat pumps, smart thermostats), renew and refurbish homes/buildings, use electrical and sustainable mobility.

Grid interactions Smart Grids are an enhancement of the existing electricity network by the introduction of new functionality such as self-haeling, Secure Electricity Supply, interactivity because it integrates both electricity and communication in an electric network, predictivity as they predict events most likely to occur, integration of distributed and renewable energy, provision of long-term sustainable power system, adoption of cleaner energy (i.e. electric vehicles).

5. POSITIVE ENERGY DISTRICT CONCEPT

To extend and shift the focus from the individual building to the neighborhood level so as to stimulate the city-wide energy transition in Europe, the concept of Positive Energy District (PED) is conceived.

Different definitions for PED are designed at European level depending on the particular organization or program. These definitions underline the nature/spirit of PEDs and the modality for their realization, even if in such definitions they are described qualitatively. In the framework of the European Joint Programming Initiative Urban Europe (JPI UE), PEDs are defined as "energy efficient and energy flexible urban areas or groups of connected buildings that produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration among different systems and infrastructures and the interaction between buildings, the users and the regional energy, mobility and ICT systems, while securing the energy supply and a good life for all in line with social, economic, and environmental sustainability" [**?**].

According to the Action 3.2 of the European Strategic Energy Technology Plan (SET-Plan), PED are districts with zero annual net energy imports and zero net CO2 emissions, which generate more renewable energy than they consume annually.They provide a) positive annual net renewable energy production, b) high energy efficiency, c) flexibility, d) diversified renewable energy technologies and e) an inclusive, affordable and sustainable lifestyle rather than economic benefits.

The JPSC of EERA has identified four types of PEDs based on both the way the energy balance is achieved and the ability to interact with energy networks, consumers and producers outside their geographical boundaries. They can be categorized as it follows [John R. Littlewood [2022]]:

- ***autonomous PED***: It meets the on-site energy demand with on-site renewable energy production and it can exports energy surplus to other PEDs, external electricity grid or district heating/gas network;
- ***dynamic PED***:It has a net positive annual renewable energy generation within the geographical boundaries and dynamic bidirectional energy trading with other PEDs as well as the external electricity grid and district heating network to compensate for momentary surpluses and shortages;
- ***virtual PED***: It has a net positive annual renewable energy generation within the virtual boundaries and dynamic bidirectional energy trading with other PEDs as well as the external electricity grid and district heating network to compensate for momentary surpluses and shortages;
- ***pre-PED (or candidate PED)***: It is unable to meet the energy demand within the geographical boundaries, and it acquires the lacking energy on the market by importing certified green energy.

6. A POSSIBLE SCENARIO

According to the EU recommendations and taking into account the need to develop energy-efficient buildings, the main goal to be pursued is the intelligent application of multi-objective approaches, taking care both to reduce energy consumption and maximize comfort offered to the occupants. The development of a technological infrastructure able to deal with big data captured both by the building monitoring system and by external systems (such as information concerning weather forecast and occupant lifestyle habits) is advisable. AI-based problem solving adopts AI technologies for data analysis, pattern identification, and provides efficient solutions to complex problems. AI models need to be trained with significant data so as to produce solutions based on analysis whose accuracy has to be validated [Joksimovic et al. [2023]].

AI-driven systems and AI-based software procedures can be installed on high-performance computer systems for the training phase, which is the most expensive activity in terms of development time and computational cost. Once the developed intelligent system has learned to find patterns and make correct predictions, it can be inserted into the control loop of the smart building. Multiple sensors and IoT devices, with which the building has been equipped, collect several types of variables (such as indoor climate conditions, acoustic conditions, and personal parameters). These acquired data are stored in a database and processed by the intelligent system to provide useful/relevant information to perform smart and informed decision-making. The solution identified the need

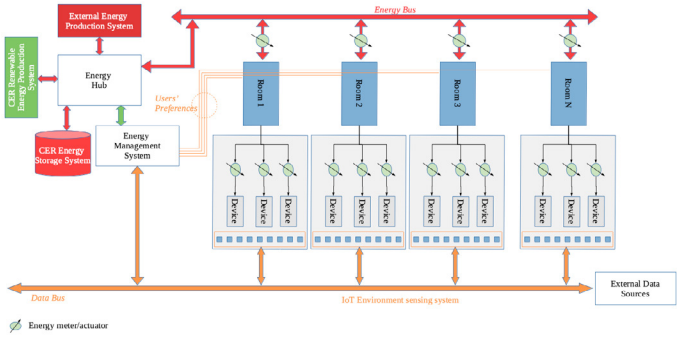

Fig. 1. Scheme of a closed-loop smart energy management system data acquisition/processing/actuation. Sensors inside each room collect the local status and feed it to the intelligent system whose goal is the definition of the best actuation profile to guarantee the twin goal for the smart building

for an ongoing monitoring to secure a behavior in line with expectations.

Dynamic adjustments of the system, as a result of changes in the conditions to be monitored, are necessary to meet design specs. For example, in this way energy consumption and operational costs can be lowered while ensuring a high comfort level for occupants.

The actuation network could be very complex, depending on the number of active regulations scheduled in each building's room. For example, assuming an office building, indoor light and temperature, air quality, presence/absence of workers and their number, and worker parameters should be some of the variables to be monitored. Such data, along with the user's settings, should be processed for all the office rooms. Data acquired by sensors represents the instant variable dataset that should be used to obtain the best "actuation profile" to control several devices.

Based on the set building actuation profile, the AI-driven system should be able to forecast the value of some "figure of merit" for a specified time-interval selected by the user (for instance, the power consumption within 24 hours). A general scheme of such a structure is sketched in figure 1.

The observed data compose a high-dimensional hyperspace, having the parameters measured by sensors as dimensions. To optimize the intelligent system design in terms of cost and complexity, a decrease in the space dimensionality would be desirable and advisable. Among known intelligent techniques, a deep learning approach could be selected and, in particular, Long-Short Term Memory (LSTM), [LST [2022]], and/or efficient Autoencoders [Berahmand [2024], 39 [2021]] are good candidates.

An LSTM neural network is a type of recurrent neural network that can remember information for a long time and apply that stored data for future calculations. Due to the presence of feedback connections, entire sequences of data can be processed, making them able to understand and predict patterns in sequential data [Widodo and Djuniadi [2021]]. Auto-encoders are a specific type of feedforward neural networks that compress the input into a lower-dimensional code and then reconstruct the output from this representation, so that such systems can take decision by observing specifically a few (combinations) of parameters, instead of the complete set of observed data.

7. CONCLUSION

Environmental sustainability has become a particular focus of attention and a necessity that can no longer be postponed. In this context, sustainable and smart buildings represent a promising way of achieving energy efficiency, occupant well-being, and overall resource optimization. Smart buildings integrate advanced technologies, interconnected systems, and data-driven strategies to create an intelligent/eco-friendly infrastructure.

In this contribution, the fundamental and necessary methodological steps to be carried out for identifying the optimal elements of positive energy districs are highlighted. In particular, cross-sectional study of European Union documents and legislative measures about building performances, scientific research outcomes, technical standard development based on knowledge resources identify the key elements of smart sustainable buildings in PEDs.

Smart Building development is still challenging due to structural barrier and barriers associated with innovation and technology. Necessity of qualified and specialized professionals, higher construction costs with respect to those of traditional buildings, resistance in changing traditional practices, difficulties to access financing and sufficient economic resources are some of the obstacles yet to be overcome.

REFERENCES

(2020). URL `https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en`.

(2021). URL `https://www.analyticsvidhya.com/blog/2021/03/introduction-to-long-short-term-memory-lstm/`.

(2022). URL `https://www.deeplearningbook.org/contents/autoencoders.html`.

Affonso, E.O.T.; Branco, R.M.O.G.A.C.C.H.A.S.C. (2024). The main barriers limiting the development of smart buildings. *Buildings*, 14.

Apanavi, R., S.M. (2023). Key factors affecting smart building integration into smart city: Technological aspects. *Smart Cities*, 6.

Baharetha, S.; Soliman, A.H.M.A.A.E.M. (2024). Assessment of the challenges influencing the adoption of smart building technologies. *Front. Built Environ.*, 9.

Berahmand, K., D.F.S.E.e.a. (2024). Autoencoders and their applications in machine learning: a survey. *Artif Intell Rev*, 57. URL `10.1007/s10462-023-10662-6`.

Biyik, E., K.A. (2019). A predictive control strategy for optimal management of peak load, thermal comfort, energy storage and renewables in multi-zone buildings. *Build. Eng.*, 25.

Chen, Y., Huang, D., Liu, Z., Osmani, M., and Demian, P. (2022). Construction 4.0, industry 4.0, and building information modeling (bim) for sustainable building development within

the smart city. *Sustainability*, 14(16). URL https://www.mdpi.com/2071-1050/14/16/10028.

Domingos, L., S.M.R.R.P.M.B.R.S. and Ferreira, R. (2024). Establishment of a smart building assessment framework in the context of smart cities. *Built Environment Project and Asset Management*, 14(5).

Jaradat, H., Alshboul, O.A.M., Obeidat, I.M., and Zoubi, M.K. (2024). Green building, carbon emission, and environmental sustainability of construction industry in jordan: Awareness, actions and barriers. *Ain Shams Engineering Journal*, 15(2), 102441. doi:10.1016/j.asej.2023.102441. URL https://www.sciencedirect.com/science/article/pii/S2090447923003301.

John R. Littlewood, Robert J. Howlett, L.C.J. (2022). *https://link.springer.com/book/10.1007/978-981-16-6269-0*.

Joksimovic, S., Ifenthaler, D., Marrone, R., De Laat, M., and Siemens, G. (2023). Opportunities of artificial intelligence for supporting complex problem-solving: Findings from a scoping review. *Computers and Education: Artificial Intelligence*, 4, 100138. doi:10.1016/j.caeai.2023.100138. URL https://www.sciencedirect.com/science/article/pii/S2666920X23000176.

jpi urbaneurope.eu/ (2024). URL wpcontent/uploads/2021/10/setplan$_s$*martcities_implementationplan*-2.*pdf*.

Karg, B. and Lucia, S. (2018). Deep learning-based embedded mixed-integer model predictive control. *European Control Conference (ECC)*.

Megahed, T.F., A.S.Z.A. (2019). Energy management in zero-energy building using neural network predictive control. *IEEE Internet Things*, 6(3).

Ming, R., Y.W.Z.X.L.Y.L.B.E.E.Y.R. (2020). Assessing energy saving potentials of office buildings based on adaptive thermal comfort using a trackingbased method. *Energy Build.*, 208.

Moretti, E. and Stamponi, E. (2023). The renewable energy communities in italy and the role of public administrations: The experience of the municipality of assisi between challenges and opportunities. *Sustainability*, 15(15). doi:10.3390/su151511869. URL https://www.mdpi.com/2071-1050/15/15/11869.

Mousavi, S., Villarreal-Marroquín, M.G., Hajiaghaei-Keshteli, M., and Smith, N.R. (2023). Data-driven prediction and optimization toward net-zero and positive-energy buildings: A systematic review. *Building and Environment*, 242, 110578. doi:10.1016/j.buildenv.2023.110578. URL https://www.sciencedirect.com/science/article/pii/S0360132323006054.

Ohene, E., Chan, A.P., and Darko, A. (2022). Review of global research advances towards net-zero emissions buildings. *Energy and Buildings*, 266, 112142. doi:10.1016/j.enbuild.2022.112142. URL https://www.sciencedirect.com/science/article/pii/S0378778822003139.

Olabi, A.G., Shehata, N., Issa, U.H., Mohamed, O., Mahmoud, M., Abdelkareem, M.A., and Abdelzaher, M. (2025). The role of green buildings in achieving the sustainable development goals. *International Journal of Thermofluids*, 25, 101002. doi:10.1016/j.ijft.2024.101002. URL https://www.sciencedirect.com/science/article/pii/S2666202724004415.

Parra-Domínguez, J., Sánchez, E., and Ordóñez, (2023). The prosumer: A systematic review of the new paradigm in energy and sustainable development. *Sustainability*, 15(13). doi:10.3390/su151310552. URL https://www.mdpi.com/2071-1050/15/13/10552.

Pasquale Capezzuto, Graziano De Scisciolo, C.G. (November, 21, 2024). Smart sustainable principles design.

Reynolds, J., R.Y.K.A.P.S. (2018). A zone-level, building energy optimisation combining an artificial neural network, a genetic algorithm, and model predictive control. *Energy*, 151.

Ruusu, R., C.S.D.B.H.A. (2019). Direct quantification of multiple-source energy flexibility in a residential building using a new model predictive high-level controller. *Energy Convers. Manag.*, 180.

Sartori, I., Napolitano, A., and Voss, K. (2012). Net zero energy buildings: A consistent definition framework. *Energy and Buildings*, 48, 220–232. doi:10.1016/j.enbuild.2012.01.032. URL https://www.sciencedirect.com/science/article/pii/S0378778812000497.

Silva, B.N., Khan, M., and Han, K. (2018). Towards sustainable smart cities: A review of trends, architectures, components, and open challenges in smart cities. *Sustainable Cities and Society*, 38, 697–713. doi:10.1016/j.scs.2018.01.053. URL https://www.sciencedirect.com/science/article/pii/S2210670717311125.

Widodo, D.A., I.N.U.E.D. and Djuniadi (2021). doi:10.1088/1755-1315/700/1/012026. URL https://www.analyticsvidhya.com/blog/2021/03/introduction-to-long-short-term-memory-lstm/.

Wu, W. and Skye, H.M. (2021). Residential net-zero energy buildings: Review and perspective. *Renewable and Sustainable Energy Reviews*, 142, 110859. doi:10.1016/j.rser.2021.110859. URL www.sciencedirect.com/science/article/pii/S1364032121001532.

Yuekuan Zhou, J.L. (2024). Advances in emerging digital technologies for energy efficiency and energy integration in smart cities. *Energy Buildings*, 315. doi:10.1016/j.enbuild.2024.114289.