# D5.1. Development of sustainable strategies for Net Zero Energy Buildings and Energy Awareness using Smart Appliances

## WP5 – Green Economy Models and Management Systems

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## Table of Contents

## List of abbreviations

| | |
|---|---|
| BEN | Beneficiary |
| Dn | Deliverable (number) |
| DoA | Description of Action |
| DS | Doctoral School |
| ESR | Early Stage Researcher |
| ETN | European Training Network |
| GA | Grant Agreement |
| IRP | Individual Research Project |
| ITN | Innovative Training Network |
| MSn | Milestone (number) |
| MSCA | Marie Sklodowska-Curie Actions |
| PC | Project Coordinator |
| REC | Research Ethics Committee |
| RSC | Recruitment and Secondment Committee |
| WPn | Work Package (number) |

# 1. Executive summary

The Work Package (WP5) focuses on supporting and coordinating research and application of business models in collaborative renewable energy systems, microgrids, and energy management. It aims to demonstrate the benefits of WP2, WP3, and WP4 technologies by designing synergic strategies and providing policy suggestions for transforming energy systems. Within the given scope, this document contains a comprehensive report on the "Development of Sustainable Strategies for Net Zero Energy Buildings and Energy Awareness using Smart Appliances" that covers task 5.1.

Net Zero Energy Buildings (NZEBs) have been distinguished by exceptional energy efficiency specifications, producing as much energy as they consume over a year. These buildings present numerous advantages, such as decreased energy usage, diminished greenhouse gas emissions, enhanced indoor air quality, and heightened comfort levels for inhabitants. The report starts by analysing the latest advancements in sustainable methodologies applicable to NZEBs, encompassing passive and active techniques, energy-saving initiatives, and the fusion of renewable energy resources. Furthermore, the report presents several frameworks rooted in optimization-based techniques. These frameworks are crafted to implement sustainable strategies, ensuring the achievement of technical, economic, and environmental objectives within energy management systems. Specifically tailored for optimal NZEB operation, these frameworks leverage Mathematical Programming (MP) models to simulate real-time facility operation and energy flow. To validate the efficacy of these frameworks, extensive simulations using numerical approaches have been conducted. The results of these simulations affirm the economic viability, environmental consciousness, and technical flexibility of the frameworks.

## 1.1. Objectives of the deliverable

The core aim of this deliverable is to furnish a detailed report on sustainable strategies for NZEBs and the integration of energy awareness using smart appliances. This entails a thorough examination of state-of-the-art approaches, encompassing passive architectural design, active strategies, and the incorporation of renewable energies, as detailed in the 3.1 subsections. Also, Smart Grids play a vital role in enabling NZEBs to actively participate in energy markets and increase user participation in energy management. This mutual connection between NZEBs and the grid, facilitated by smart grid infrastructure, allows for real-time management of energy usage based on dynamic grid signals. Furthermore, it offers the incorporation of renewable energy sources such as solar and wind into NZEB. This bidirectional flow of energy enables NZEBs to optimize their consumption profiles, potentially feeding extra clean energy back into the grid, improving overall sustainability and driving a shift to a more environmentally friendly energy landscape. Also, smart grids provide users with detailed information on their energy use patterns via smart appliances. This data transparency supports energy-conscious behaviour, ultimately contributing to the improved sustainability performance of NZEBs. A summary of NZEB status within the framework of smart grid technology is deliberated accordingly.

The deliverable aims to present novel strategies derived from optimization-based frameworks tailored for NZEBs alongside with their verification procedures through conducted simulations, as reported in the 3.2 section. The overall schematic of the developing process is demonstrated in Figure 1. Within the NZEB context, energy management systems act as decision-makers responsible for managing the operational aspects of buildings, including scheduling appliances and facilities, as well as regulating interactions with utility grids. Hence, deploying a sustainable strategy requires translating the strategy for these systems through implementation frameworks. These frameworks are aligned with strategies devised using various modelling techniques and approaches, namely optimization-based methodologies and machine learning techniques. Furthermore, when considering energy communities, the scope of the frameworks can encompass single buildings or community members, such as a cluster of interconnected buildings. While a single building's energy modulation capability appears limited, the collective potential of buildings aggregated within energy communities or through aggregators is significant. This collaborative approach allows for significant alterations in energy consumption profiles, making it easier to provide vital grid ancillary services such as demand response and power balancing. Thus, while individual buildings' inherent flexibility might be restricted, the synergistic impact gained by aggregation considerably improves the overall stability and efficiency of the electricity grid. Also, each strategy is meticulously described through its mathematical formulation, accompanied by a thorough assessment of its effectiveness. Through the synthesis of theoretical frameworks and simulation-based assessments, the deliverable seeks to contribute valuable insights and recommendations for the successful implementation of sustainable strategies in the context of NZEBs and energy awareness.

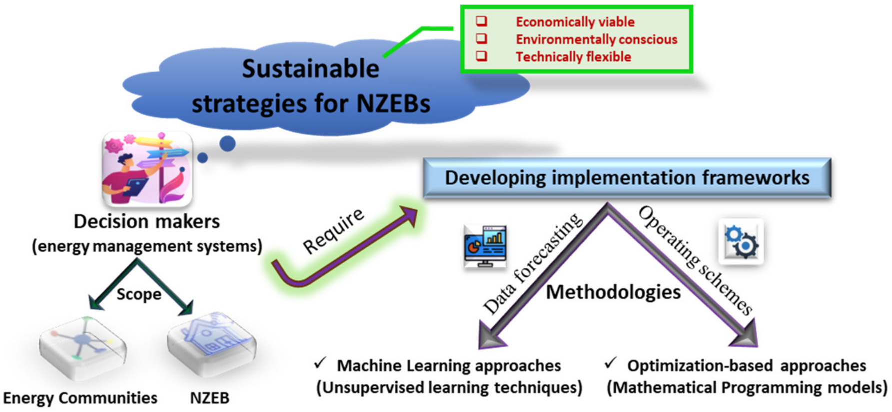

Figure 1. The overall outline of the development process.

# 2. General progress of the action

## 2.1. WP5 Objectives and tasks

The deliverable is part of WP5 "Green Economy Models and Management Systems" which focuses on innovative energy management tools and business models for addressing the new challenges stated by the electric energy system. Four Individual Research Projects (IRPs) are involved in WP5 focusing on different research topics concerning innovative management solutions and business models. In detail, IRP12 focuses on sustainable strategies for Net Zero Energy Buildings and energy flexibility services, IRP13 focuses on digital twins for optimising energy self-production and self-consumption, IRP14 focuses on new integrated services for distributed electric energy systems, and IRP15 focuses on designing business models for Energy Communities. The research outputs will contribute to a better understanding and diffusion of technological and business solutions to foster the sustainable energy transition. In detail, WP5 has 3 goals, listed below:

1. Supporting and advancing the synergies between WP2, WP3, and WP4 in business model research, evaluation, and validation to facilitate cooperative and distributed renewable generation systems, microgrids, energy management, and consumption control systems.
2. Developing synergic strategies to display the benefits of systems and technologies developed in WP2, WP3 and WP4.
3. Suggesting policy recommendations to guide the transition of the energy system.

WP5 included 5 Tasks which involves different SmartGYsum partners:

- Task 5.1: Development of sustainable strategies for Net Zero Energy Buildings and Energy Awareness using Smart Appliances (UNL, UB).
- Task 5.2: Generation of digital twins of prosumers using socioeconomical factors and big data for Optimization of Customer's bill savings, (UB-SIEM-UNL).
- Task 5.3: Energy value chains and markets developed with the new paradigm of distributed EES (UB -CNR-UNL).
- Task 5.4: Identifying enablers and barriers to foster the replicability and transfer of business models for Green Energy Systems (UB, ECPE, UNL).
- Task 5.5: Elaboration of partial and final scientific reports (UB).

This deliverable is part of the Task 5.1 and report the main fundings of the IRP12 "Development of sustainable strategies for Net Zero Energy Buildings and User Energy Awareness using Smart Appliances".

## 2.2. WP5 – IRP progress

IRP12 aims to "develop sustainable strategies for Net Zero Energy Buildings (NZEB) and User Energy Awareness using Smart Appliances". NZEBs refer to buildings with extremely high energy performance, where energy from renewable sources—including energy produced on-site or nearby—should account for a very large portion of the almost zero or extremely low amount of energy needed. NZEBs can employ both passive and active strategies. The passive strategies describe how architectural design techniques are used in the early design phase of a structure to reduce its energy demand, including its heating and cooling loads, and can be subdivided into Passive Sustainable Design (PSD) and Energy-Saving Techniques (EST). The PSD can minimize the energy demand of a building by focusing on geographical and meteorological factors, while the EST aims to decrease energy demand by improving capabilities for sealing and insulating by using enhanced building materials like thermal insulation and shading. On the other hand, the active strategies deploy energy management strategies and incorporate RERs in order to control the load. Moreover, NZEBs are capable of providing energy flexibility services that can be utilized in the energy market by third parties as auxiliary services. Energy flexibility refers to the capacity of a building to control its energy generation and consumption in accordance with user demands, grid requirements, and local climate conditions. Building energy flexibility will therefore enable demand response based on the demands of the surrounding networks, as well as demand side management and load control.

The IRP12, so far, mostly focuses on active strategies for NZEBs; however, he also considers passive strategies related to EST. In detail, in IRP12, two sustainable strategies for NZEBs have been developed. The first strategy involved collaborative stochastic energy management of interconnected Energy Hubs (EH) with a focus on environmental factors. The second strategy involved the development of a methodology for efficient energy flow management in residential buildings to schedule shiftable appliances and energy storage. This methodology explores distinct consumption strategies and introduces novel flexibility indicators to quantify the energy flexibility potential of buildings across various operational scenarios.

IRP12 main contributions to WP5 concern the sustainable strategies for NZEBs developed in this research. The development and scaling up of optimal energy management strategies considering a network of NZEBs within the Energy Communities (ECs) concept, enhance the capacity to establish and develop cooperative strategies among households that can enhance the role of NZEBs. Enabling NZEBs as active players in power markets can bring economic benefits by participating in day-ahead and real-time schemes or offering flexibility in ancillary service markets. Consequently, modelling interactions among players from technical and economic perspectives is important for sustainable and secure cooperation.

IRP12 involves ESR-12 that joined SmartGYsum project on December 15, 2022. His research activities have been conducted for sixteen months since his recruitment by NOVA University of Lisbon (hosting institution). ESR-12 works in the Department of Electrical and Computer Engineering (Energy Efficiency Group) of the School of Science and Technology (FCT NOVA). Also, his focus is on using smart appliances to manage energy through user-centric approaches as well as developing collaborative strategies within the energy community framework. ESR-12 has finished the first two months of secondment at Salerno University, Italy (15 January–15 March 2024).

The deliverable is organized into sections addressing the state of the art in sustainable strategies for NZEBs. This includes an examination of existing approaches and a brief report of the conducted literature review, as presented in subsections 3.1.1 and 3.1.2. In subsection 3.1.3, there is a discussion about the current status of NZEBs within the context of smart grid technology. Furthermore, section 3.2 is dedicated to the developed strategies within the SMARTGYsum project. The latter sections of the deliverable are dedicated to drawing conclusions from the findings. Through this organization, the document aims to offer a comprehensive narrative that guides readers through the exploration of sustainable strategies for NZEBs.

# 3. Deliverable description

## 3.1. Net Zero Energy Buildings

A significant portion of the world's energy consumption and carbon emission are attributable to the building industry [1]. NZEBs emerge as a sustainable and efficient alternative to conventional buildings, aiming to minimize energy consumption and optimize energy production through Renewable Energy Resources (RER). NZEBs are specifically engineered to generate equal to or greater amounts of energy locally compared to what they consume annually. Figure 2 illustrates a schematic of basic components in a typical NZEB and its interconnections with the utility grids.

### 3.1.1. Background and motivations

A NZEB is designate by exceptionally high energy efficiency, with the remaining minimal energy needs predominantly sourced from renewables, including on-site or (locally) nearby production. Mandated by the Energy Performance of Buildings Directive, EU countries were required to guarantee that all new structures achieved nearly zero-energy status till 2021, extending to public buildings by December 31, 2018 [2], [3]. A recent proposal in December 2021 suggests advancing from NZEB to Zero-Emission Building (ZEB), aligning with long-term climate neutrality goals as well as the "energy efficiency first principle." Based on the proposed directive, a ZEB is a building with exceptional energy performance, entirely powered by RERs, and without the carbon emission related to utilizing fossil fuels on-site. The ZEB requirement is slated for implementation from the beginning of 2030, for all new structures and from the start of 2027, for those possessed or utilized by governmental entities. The directive emphasizes reducing operational greenhouse gas emissions and introduces "life-cycle Global Warming Potential (GWP) calculations", with disclosure through energy performance certificates. This requirement is expected to commence from January 1, 2027, for buildings exceeding 2000 square meters and from January 1, 2030, for all new buildings. Moreover, EU member states submit their national plans for NZEBs to the Commission, detailing approaches to increase their prevalence. The directive also requires long-term renovation strategies to economically convert existing buildings into nearly zero-energy structures. The proposed revision aims to merge these strategies into national building renovation plans with the goal of achieving zero-emission buildings throughout the building stock. The Commission oversees the progress of EU member states in boosting nearly zero-energy buildings, with guidelines established, a synthesis report produced, and subsequent studies conducted. Integrated reporting on nearly zero-energy buildings is now incorporated into National Energy and Climate Plans reporting requirements.

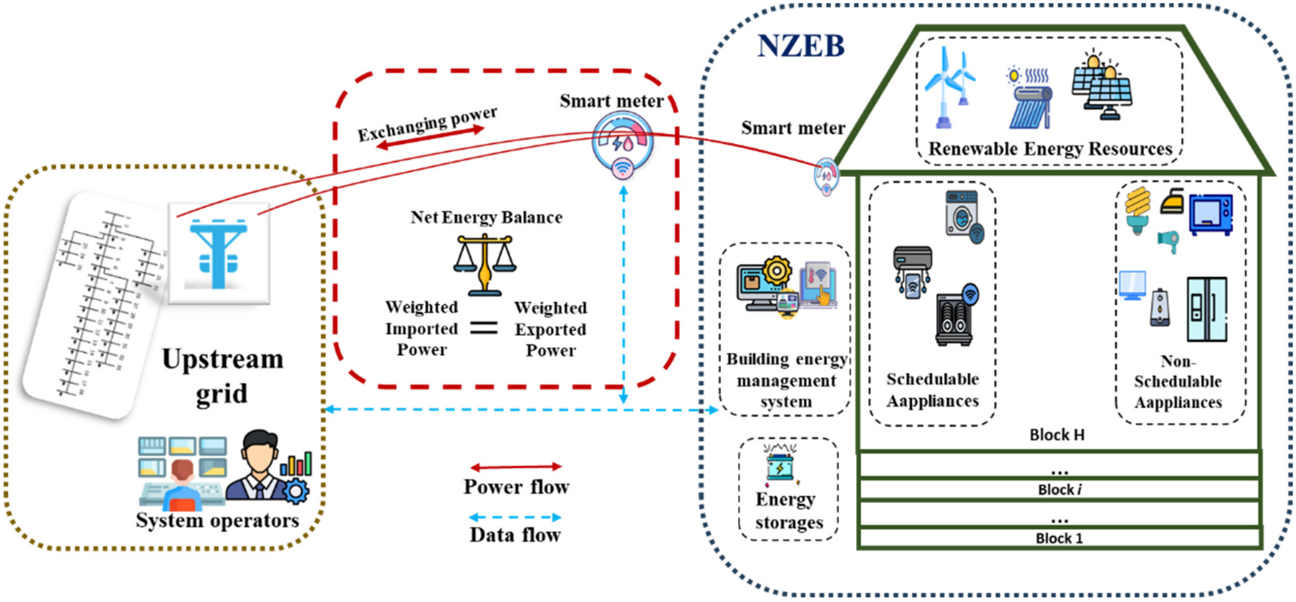

Figure 2. The schematic of the structure and basic components in NZEBs.

*Definitions and characterizations*

Regarding the definition, there is no universally accepted definition of NZEBs. However, as it has been mentioned earlier, these structures strive for energy independence by minimizing consumption and generating clean energy on-site, aiming to balance or even exceed their annual needs. Nevertheless, the definition of NZEB varies based on its intended objective. In [4], four distinct definitions have been outlined: "Net Zero Source Energy", "Net Zero Energy costs", "Net Zero Site Energy", and "Net Zero Energy Emissions". Depending on the chosen method for the energy interaction evaluation, these definitions consider the grid when measuring total energy use and allow for various RERs. Reaching a balance of zero total energy use per unit area per year often involves significant back-and-forth energy exchange between the main grid and the building [5]. Also, Figure 3 visualizes the most frequent keywords related to "NZEB" concept, extracted from the Scopus database by VOSviewer software [6]. Visualizing keywords has provided a thorough summary of the significant themes and topics linked to NZEBs that assists in recognizing trends, patterns, and research focal points, offering a clear visual depiction of the intricate network of concepts surrounding NZEBs. The size of each circle reflects the frequency of a keyword in the dataset, with larger circles indicating more frequent keywords. Notably, "energy efficiency," "energy management," "renewable energy," and "sustainability" emerge as highly correlated topics.

Moreover, it would be interesting to visualize some of the related concepts. For instance, by imagining a graph with the annual energy used by a building on the vertical axis and the embodied energy used in its construction on the horizontal axis, a perfect Zero Energy Building would fall on a diagonal line, representing equal annual energy use and embodied energy, as shown in Figure 4. Buildings closer to the horizontal axis use less energy overall, even if they use more energy for operation each year. This concept, called Life Cycle ZEB (LC-ZEB) [7], emphasizes minimizing the total energy footprint, not just operational energy.

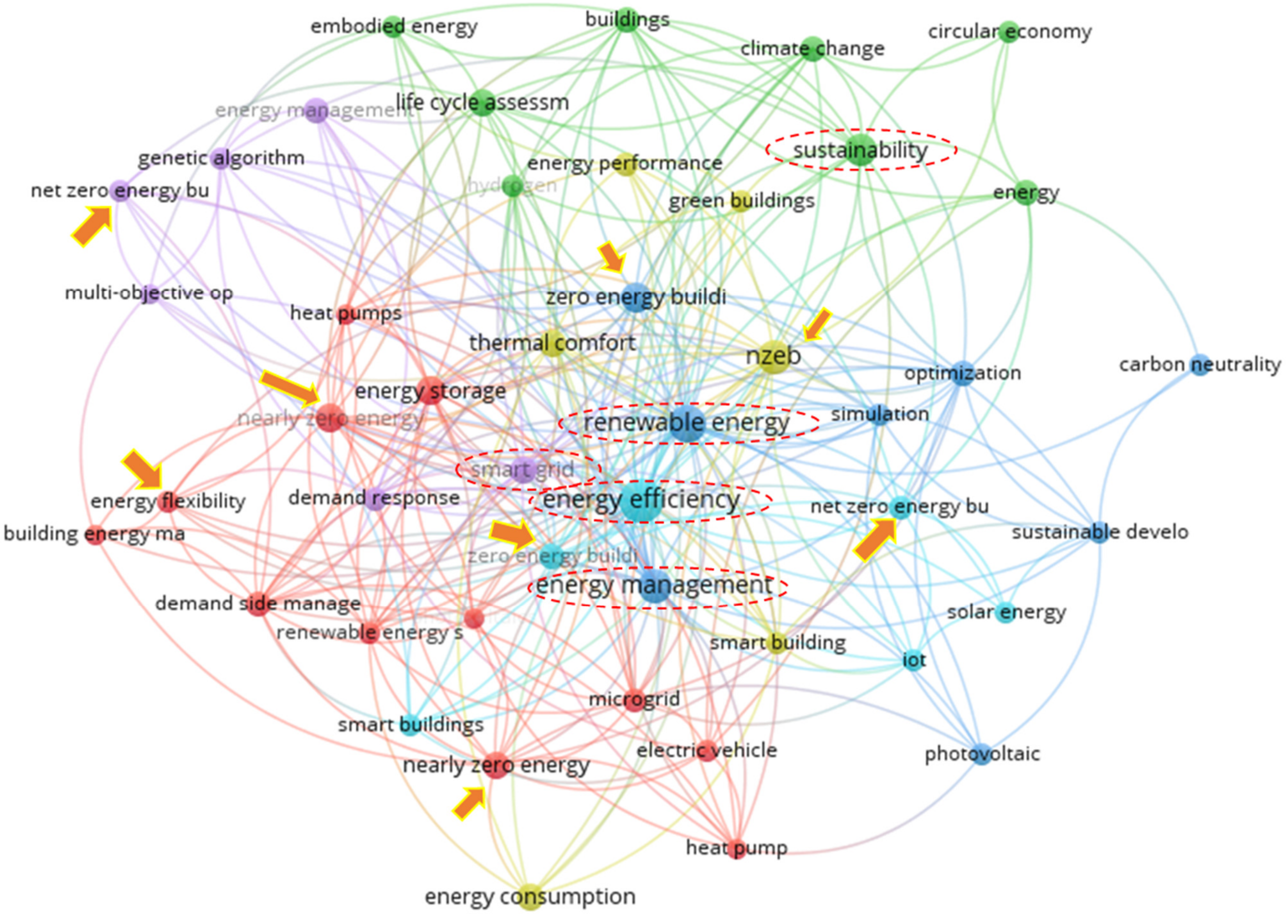

Figure 3. The variety of the main keywords regarding NZEB context.

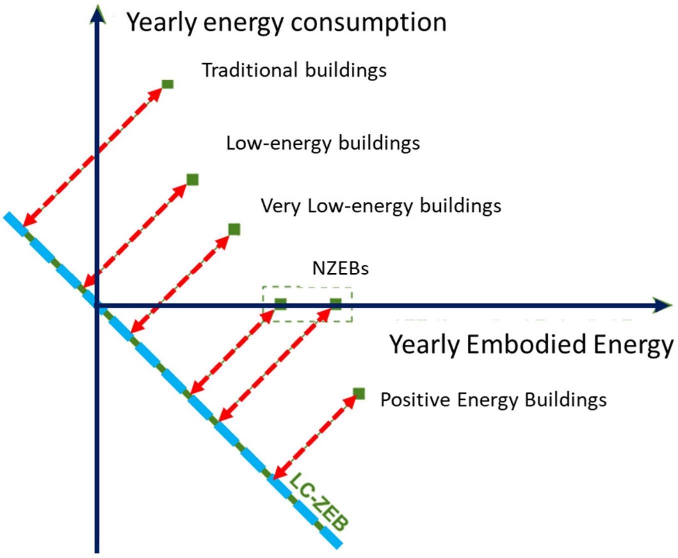

Figure 4. Visualizing the annualized life cycle energy of typical buildings [6].

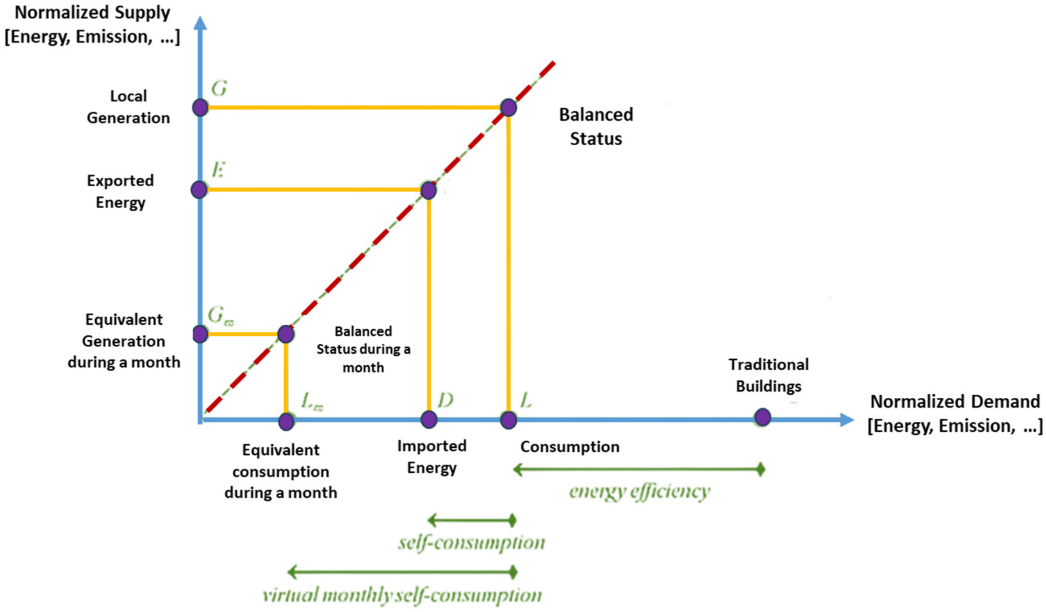

Figure 5. Visualizing a description of three energy balance points, namely import/export, consumption/generation, and net values [8].

The definition can also be visually represented, as illustrated in figure 5 [5], [8]. As shown in the graph, there is a comparison of energy use and renewable energy generation. The starting point (reference building) represents a typical building with basic energy-saving measures. This is a benchmark for comparison. Points further to the left (L, D, Lm) show buildings designed to use much less energy. These points represent different ways to obtain a balance between energy usage and generation, whether for a whole year, a specific period, or even factoring in generation vs. consumption each month [8]. On the other side of the graph (vertical axis) is the amount of renewable energy produced. Ideally, these two lines (energy use and generation) would intersect on a diagonal line, signifying perfect balance at different timeframes. Additionally, the graph can consider other factors like carbon emissions, which can be calculated based on energy use.

There are different ways to classify Zero Energy Buildings (ZEBs). Some, like *A-D* classifications, consider the type and location of renewable energy used (e.g., rooftop solar vs. off-site wind farm). This helps choose the best renewable options based on a building's location and resources [9]. However, aiming to achieve energy self-sufficiency through on-site renewable energy generation requires significant investment in technologies like solar panels and wind turbines [10]. Buildings should prioritize using renewable energy, ideally generated on-site or nearby. While perfect balance might be difficult due to various factors, there are guidelines (EPBD) for defining highly energy-efficient buildings considering local conditions. These guidelines set a specific energy use limit per square meter per year [11]. Furthermore, various definitions of zero energy buildings were presented by different authors. A widely used definition describes nZEBs as structures with considerably low energy consumption, offset by local generation employing RERs [12]. Also, there is another popular approach by which NZEBs can be classified into two main types:

- *Zero Net Energy Ready buildings*: These buildings are designed to achieve net-zero energy performance but may require some on- or off-site energy to meet their energy needs in certain years due to factors such as weather patterns and occupant use.
- *Zero Net Energy Certified buildings*: These buildings have been certified by a third-party organization as meeting the requirements of a NZEB standard, indicating that they meet the net-zero energy performance consistently.

### *Relevant standards and codes*

Professional organizations have introduced programs for rating and labelling buildings. These initiatives aim to motivate designers and proprietors to improve the buildings' sustainability, potentially leading to increased property value or prestige. These rating programs tackle a range of sustainability concerns, encompassing the utilization of recycled materials, environmental integration, minimized embodied energy, enhanced indoor air quality, and diminished energy consumption. The efficiency of buildings in terms of energy can fluctuate notably, impacted by the rigor and specifications of each accreditation and evaluation framework. Figure 6, extracted from [13], provides examples of certificate programs specifically designed for sustainable buildings. In order to fulfil the requirements, set by these certification initiatives, buildings must integrate a wide array of energy-efficient and RER technologies. Historically, the adoption rates of these technologies have shown significant variation, with certain technologies being embraced more swiftly and extensively compared to others [14].

Moreover, Smart Buildings are essential for encouraging effective energy use, which significantly lowers overall energy consumption. Consequently, buildings equipped with intelligent technologies along with Building Energy Management Systems (BEMSs) contribute to the feasibility of obtaining net-zero energy status. The pros and cons of these buildings have been outlined in Table 1 [15].

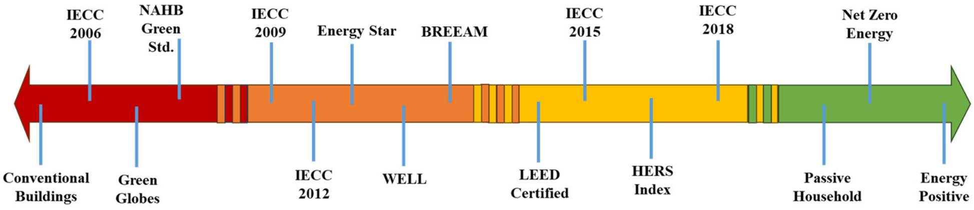

Figure 6. Evaluation of energy system standards and certificates [13].

Table 1. Pros and cons of smart NZEBs.

| Advantages | Disadvantages |
|---|---|
| **Remote and Efficient Management of Energy Systems:**<br>• Smart buildings/homes oversee energy systems and services remotely, efficiently controlling ESSs, RERs, smart appliances, HVACs, and lighting to ensure sustainable energy savings while preserving comfort.<br>• Ongoing Monitoring for Predictive Management:<br>• Energy systems are continually monitored, enabling operators to manage and predict consumption over time.<br>**Behaviour Improvement through Data Monitoring:**<br>• Operators or occupants can enhance behaviour by monitoring data.<br>**Scheduled Energy Usage in Smart NZEBs:**<br>• Smart NZEBs empower the owners to manage energy usage based on demand, facilitating interaction with smart utility grids.<br>**Insulation from Future Energy Price Increases:**<br>• Property owners who own buildings are protected from future rises in energy costs. | **Higher Initial Costs and Affordability Concerns:**<br>• These buildings/homes are more expensive than conventional ones, making them overpriced for the average individual. Nevertheless, market changes might lead to future alternatives with reasonable costs.<br>**Intensive Training Required for Renewable Systems and IHEMS:**<br>• The use and interaction with renewable systems and smart buildings/homes energy management systems will necessitate intensive training for homeowners, requiring a minimum educational level for operators.<br>**Ongoing Maintenance Costs and Service Provider Involvement:**<br>• Service providers must do routine maintenance in order to guarantee the effective running of these sophisticated, linked systems. Homeowners must allocate a specific budget for maintenance work.<br>**Limited Expertise in Designing Zero Net Energy Buildings:**<br>• Not many builders/designers have the training or experience needed to construct NZEBs.<br>**Challenges in Recovering Higher Initial Costs on Resale:** |

| | |
|---|---|
| **Enhanced Comfort through Uniform Temperatures:**<br>• Comparative isotherm maps show that more consistent interior temperatures lead to greater comfort.<br>**Reduced Need for Energy Austerity:**<br>• There is a decreased requirement for energy austerity.<br>**Cost Savings and Improved Efficiency:**<br>• A lower total cost of ownership is attained as a result of increased energy effectiveness.<br>**Lower Net Monthly Cost of Living:**<br>• The net cost of living is lower overall in smart NZEBs.<br>**Cost-Effective New Construction:**<br>• Compared to retrofitting, new building incurs less additional costs.<br>**Higher Resale Value for Zero Net Energy Buildings:**<br>• Potential buyers are looking for more NZEBs than what is now available, therefore higher resale value is expected.<br>**Increasing Value Relative to Conventional Buildings:**<br>• It is anticipated that if energy costs rise, the value of a NZEB will rise in comparison to comparable conventional structures.<br>**Potential for Expensive Retrofits:**<br>• The need for expensive retrofits for inefficient buildings may arise from expectations of future regulatory limits and carbon emission fees. | • Recovering higher initial costs upon the resale of a building is challenging, as appraisers may lack information, and their models often ignore energy factors.<br>**Climate-Specific Design Limitations:**<br>• Adaptability against future variants in ambient temperatures, whether they are lowering or rising as a result of global warming, may be restricted by climate-specific design.<br>**Enhanced Thermal Envelope for Minimal Resource Consumption:**<br>• Resource consumption and embodied energy are higher than necessary in the absence of an optimum thermal envelope.<br>**Technical complexity:**<br>• NZEBs can be more complex to design and construct than traditional buildings due to the integration of RERs, energy efficiency measures, and smart building technologies.<br>**Lack of standardized building regulations and codes:**<br>• There is no one-size-fits-all NZEB standard, and regulations can vary from country to country, making it difficult for builders and homeowners to know what is required to build an NZEB.<br>**Lack of public awareness:**<br>• There is not a lot of public awareness of NZEBs, and many people are not aware of the benefits of these buildings |

### 3.1.2. Advanced Strategies for Net Zero Energy Buildings

Aiming to explore the advanced strategies for NZEBs' deployment and operation over the past decade, a literature survey has been accomplished. Hence, a Systematic Literature Review (SLR) methodology has been employed to identify relevant literature using the Scopus database, focusing on publications in English between 2014 and 2024. This timeframe selection aimed to capture the latest advancements in the field. However, to ensure a comprehensive understanding of core concepts, foundational references published before 2014 have been occasionally included. The results of this SLR have been detailed and reported in preparing the scientific outcomes of IRP-12 in [16], [17], and other upcoming articles. Additionally, this analysis is organized into two perspectives. First part is focusing on passive strategies, and the second one covering active strategies. This categorization has been widely used un the literature. The graphical representation of this classification is depicted in Figure 7.

*Passive strategies:*

This involves achieving NZEBs by diminishing the energy demand of building, including heating and cooling loads, through the incorporation of architectural design methods during the initial design phase. It can be further categorized into the following two sections, namely Energy-Saving Techniques (EST) and Passive Sustainable Design (PSD). Research on the implementation of NZEB through passive strategies has primarily been categorized into two groups, focusing on PSD and EST. PSD involves minimizing the energy demand of building by examining geographical and meteorological factors such as longitude, latitude, altitude, atmospheric variables (temperature, wind speed, etc.). On the other hand, EST within passive strategies aims to decrease energy demand by improving capabilities for sealing and insulating by using enhanced building materials like thermal insulation and shading.

*Active strategies:*

Once passive solutions have been put in place to reduce the energy demand of buildings, active strategies such as adopting energy management strategies and incorporating RERs can be deployed to control the remaining load. Thus, active strategies for attaining NZEB can be divided into two primary categories: RERs, and supplementary systems that include energy management systems, smart appliances, and backup solutions in place of RER.

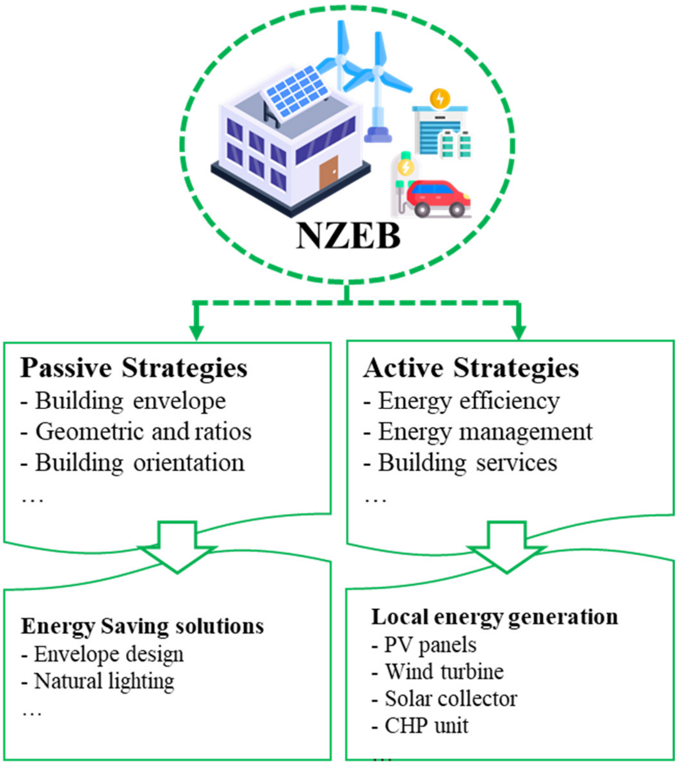

Figure 7. Strategies categorization towards achieving NZEBs.

### 3.1.3. Overview of NZEB in the concept of smart grid

Ubiquitous computing empowers smart buildings to deliver context-sensitive services, optimizing occupant well-being, safety, security, and resource management. Residential smart homes, the most prevalent and energy-intensive building type, represent the vanguard of this movement. Seamless data exchange and command interactions with the Smart Grid (SG) enable these homes to achieve significant energy savings. The SG, a two-way electrical infrastructure, uses intelligent technologies and secure communication protocols to enable efficient and secure energy transmission throughout the grid, from generation to consumption. SGs empower NZEBs to control energy usage in response to grid signals and include RERs such as solar panels and wind turbines by allowing for conversation in both directions between buildings and the grid. This capacity enables NZEBs to optimise energy consumption and feed surplus energy back into the grid, boosting sustainability and promoting a greener energy future. Furthermore, SGs let consumers to receive insights into their energy use patterns via smart appliances, encouraging energy-conscious behaviour and improving the sustainability of NZEBs.

The term "smart home" refers to a variety of functionalities inside a technologically advanced living environment. Automation, adaptability, multifunctionality, occupant comfort, self-adjusting capacities, interactivity, and overall resource efficiency are all important qualities. Smart Home Energy Management Systems (HEMS) have emerged as the foundation for effective monitoring, control, and optimization of power generation, storage, and use in smart homes. Integrating RERs and Home ESSs (HESSs) into these SG-connected households is crucial for reducing peak-demand pressures and increasing overall energy efficiency [13]. This HEMS serves as a central controller for optimizing energy consumption in a smart structure. A basic algorithm in the SHEMS collects real-time energy data from the SG while preserving privacy issues, which may include information on RERs. This information is then evaluated and converted into actionable commands for HESSs. The user interface on the main panel provides pertinent information and enables for customization. Finally, the HEMS sends commands to smart appliances, potentially shifting energy consumption to periods of lower cost or greater availability of renewable energy. This feedback loop, which is based on sensor data and user preferences, promotes occupant comfort while aiming for cost and energy efficiency.

The SG acts as the system's foundation in both centralized and decentralized manners, including DERs, e.g. RERs, ESSs, DGs.  Moreover, RERs provide a more sustainable and ecologically friendly alternative to conventional power generating. However, incorporating them necessitates modifying the current grid infrastructure [19]. In addition to the SG, HESSs play an important role. Their charging and discharging procedures are critical for efficiently coordinating these RERs with utility providers. This partnership gives the HEMS more flexibility to optimize energy use in the smart building/home, potentially lowering costs and conserving energy through judicious use of the SG. The energy management controller serves as the system's intelligent core. It functions as the brain, receiving real-time data from the SG, house sensors, and user preferences through the user interface. This extensive data enables the controller built-in optimization system to make optimal decisions. By proactively controlling numerous smart appliances within the home, the system prioritizes multiple objectives such as increasing energy efficiency, minimizing peak demand on the grid, and ensuring user comfort. Smart appliances function as the system's "output." These ordinary objects, ranging from refrigerators to thermostats, are equipped with intelligence and communication capabilities. They use Internet of Things (IoT) technology to communicate with one another, the central controller, and the wider internet. These appliances can not only offer operational data, but also understand and respond to control commands after basic manipulation using their built-in intelligence. The system's control center is a user-friendly interface, most commonly a display or smartphone app. This interface, also known as the DR dashboard, shows data from the smart grid (SG), current energy use details, user preferences, and even energy bills. Some systems allow consumers to directly arrange appliance operation for maximum comfort. Finally, a network of sensors and measurement devices serves as feedback. These sensors monitor changes in numerous physical characteristics, e.g. indoor variables and occupancy. They then turn the data into electrical impulses and send them to the central controller. This real-time data on individual appliance usage and user behavior allows the system to precisely monitor, regulate, and schedule smart appliances, hence optimizing energy consumption in the structure. HEMS frequently use smart meters. These meters facilitate real-time communication between households and energy companies. This two-way connection allows customers to not only view their current energy usage, but also access extensive past data and analyze their consumption patterns, offering vital insights for energy management. Also, HEMS is based on a powerful communication network that serves as its central nervous system. This network, also known as the HEMS infrastructure, connects all of the components: the smart meter, the smart grid, smart appliances, and even other smart devices in the home. Advances in wireless and wired technology have enabled the seamless integration of a large number of these devices. Wi-Fi, standard networking cables, HomePlug (powerline communication), Bluetooth, and Zigbee are examples of common technologies that facilitate home network (Home Area Network or HAN) connectivity.

### *Smart appliances*

A smart appliance is defined as a device equipped with communication and information features, allowing for automatic or remote operation based on user settings or external signals from energy providers. Through a HAN, smart appliances can connect with other consumer devices or networks, facilitating seamless interaction with utility systems.

A smart appliance is more than simply a refrigerator or washing machine; it is a linked gadget. For instance, a refrigerator that can automatically regulate its temperature based on how full it is, or a washing machine that can be started remotely from one's phone improves residents' comfort. All of this is made possible by smart appliances' communication and information capabilities. They can serve as assistants, and be designed to function according to individual preferences or to respond to external signals from utilities. For example, a smart thermostat could automatically adjust the temperature according to the occupancy status to save energy. Furthermore, through a collaboration scheme, smart appliances can connect with other devices. This allows them to share information and operate together more efficiently. For instance, smart lights might dim automatically when a smart TV turns on, leading to enhanced user comfort. Moreover, applying two-way communication allows utility companies to send signals to smart appliances, like suggesting off-peak hours for running your dishwasher to save on energy costs.

### *User interfaces*

HEMSs rely primarily on user interfaces (UIs). The UI functions as a central information unit, giving residents real-time data on appliance energy use, device status, and possibly even access to research studies or dynamic energy pricing models [Ref 88]. Users can use the UI to set energy preferences and priorities, thereby acting as a control centre for maximizing HEMS functionality. Modern user interfaces generally use touchscreens and provide remote access via smartphone or tablet. The efficacy of these interfaces in encouraging energy-saving behaviour has been investigated. Research done in the Netherlands examined user behaviour after 15 months of using a home energy meter. The study found that throughout the first four months, power consumption decreased by 7.8% [67]. However, the study also found that individuals differed in their ability to maintain these savings, highlighting the importance of user-friendly interfaces in driving long-term habit change. Additional study has focused on various technologies for residential energy monitoring and management. These technologies range from portable plug-in monitors for specific appliances to whole-house systems that track total energy consumption, with some even enabling appliance-level disaggregation [68]. The best system is chosen by striking a balance between usability, price, and the level of detail required for educated decision-making about household energy consumption.

*Sensors and communication systems*

HEMS rely on sensors for sensory input. They continuously send vital data points to the controller, including current, voltage, temperature, and even occupancy. This real-time information enables the controller to make sophisticated decisions about energy usage and optimization. HEMS uses smart meters, which can be centralized within the home or dispersed across various appliances. This allows the system to collect precise energy use statistics, which aids scheduling and conservation efforts. Additionally, HANs contribute to the smart home's nervous system. These networks link numerous smart appliances, including lights, electronics, monitoring software, and even security systems, to the central SHEMS controller. Wired or wireless connections connect all devices to a central access point, which is frequently a hub, node, or router. More advanced HANs combine a smart meter with a network of thermostats and other smart devices. These networks use a common communication protocol, whether wired or wireless, to seamlessly integrate appliances and equipment. This category covers hubs, portals, operating systems, network management tools, and information systems. This extensive connection enables advanced home automation and power management features [69].

*Energy Awareness*

In today's energy-dependent world, energy awareness has emerged as a critical cornerstone of sustainable living. It is the ability to recognize and understand energy consumption patterns, enabling informed decisions that optimize resource utilization. This mindset shift encourages individuals, communities, and businesses to embrace resource-efficient practices and renewable energy solutions.

Energy awareness goes beyond theoretical knowledge; it is a driving force for action. Simple yet impactful changes in daily habits can collectively make a significant difference. Turning off lights when not in use, unplugging electronics when not in operation, and utilizing energy-efficient appliances are just a few examples of energy-conscious practices. Furthermore, opting for energy-efficient lightbulbs, maximizing natural daylight, and adjusting thermostat settings can further reduce energy consumption. These seemingly minor adjustments can translate into substantial savings on utility bills and a reduced environmental footprint. The importance of energy awareness extends beyond individual actions. Fostering a collective commitment to energy efficiency at community and business levels is equally crucial. Communities can implement energy-saving measures in public buildings, parks, and streets, while businesses can invest in energy-efficient technologies and practices to lower their operating costs and environmental impact. Technology plays a pivotal role in promoting energy awareness. Smart meters provide real-time energy consumption data, empowering individuals to track their usage and identify areas for improvement. Energy-saving apps and software can assist in scheduling HVAC systems, optimizing lighting patterns, and reducing energy waste. Achieving a sustainable future requires a shared responsibility among all stakeholders. Educational institutions can integrate energy awareness into curricula, while businesses can promote energy-efficient practices among their employees. Governments can enact policies that incentivize energy conservation and invest in renewable energy infrastructure.

## 3.2. The developed sustainable strategies

In the preceding sections, an overview of the advanced strategies by the researchers for NZEBs has been reported, along with their significance within SG framework. As mentioned earlier, SGs are crucial in enabling NZEBs to actively engage in energy markets and raise energy awareness. In this section, the strategies that have been developed during the SMARTGYsum project, by ESR-12, are presented. Specifically, two active strategies have been reported in subsections *3.2.1* and *3.2.2* aiming to reduce energy bills, improve technical performance, and mitigate environmental concerns within SG context. Additionally, the subsequent subsections provide an overview of the identified problem and the proposed strategy developed to address it effectively. Furthermore, it is worth mentioning that more details regarding the mathematical model of the strategies, the validation process, and simulation results are available in the related reference papers provided within the text.

### 3.2.1. Collaborative stochastic energy management of interconnected energy hubs with a focus on environmental factors

Buildings are multifaceted structures with diverse energy demands, encompassing power consumption, heating requirements, and cooling needs. To efficiently provide these varied loads and ensure optimal utilization of resources, it is advantageous to adopt a unified approach for managing energy flow within buildings. By integrating the management of power, heating, and cooling loads, it is possible to optimize energy usage, minimize loss, and enhance the overall performance of buildings compared to supplying them separately. Moreover, the integrating approach not only improves operational efficiency but also contributes to cost savings and environmental sustainability. Buildings can be seen as Energy Hubs (EHs) that promote collaboration between various energy resources and technologies, thereby increasing resilience and efficiency. Consequently, by enabling integrated energy management, this approach promotes the development of smart, sustainable buildings. Basically, an EH functions as a system that caters to several energy needs by linking multiple energy carriers through energy conversion units, namely microturbines, chillers, CHPs, and ESSs such as electricity, heating, and ice storage. An overall schematic of the structure of an EH is illustrated in Figure 8.

NZEBs, similar to hubs, would effectively integrate multiple energy sources as well as storage systems, and coordinate consumption patterns. This reflects the necessity for an EH's ability to balance incoming and outgoing energy flows while optimizing resource use. In NZEBs, renewable energies function as the primary energy source, similar to the hub's power input. Energy storage technologies, such as batteries or thermal storage systems, work similarly to the EH's ability to store and manage energy during demand changes. The intricate network of energy demand within the building corresponds to the interconnection of nodes in a hub structure, where energy is dispersed based on various demands and priorities. Thus, seeing the energy management problem of NZEBs as an EH emphasizes the significance of holistic integration, dynamic optimization, and adaptive control solutions in achieving efficient and sustainable energy results.

Also, a reliable and efficient energy system is critical to modern society. While a single building's energy flexibility might appear modest, considering groups of users within energy communities or aggregators reveals a far more significant potential. Individual modifications in energy use or contributions of excess energy from a single building could appear minor. When numerous buildings are integrated, their adaptability becomes substantial. This allows for significant changes in energy use and the provision of vital grid services such as demand response or balancing. As a result, cooperation and collaboration through energy communities or aggregators are critical for unlocking collective potential and greatly improving power grid stability and efficiency.

By considering NZEBs as an energy hub, while existing literature has explored the problem of optimal energy management within EHs, there remains a gap in developing a cooperative strategy for Networked EHs (NEHs), as an energy community, that prioritizes environmental considerations and accounts for system uncertainties. Hence, a cooperative strategy is developed through a clustering-based probabilistic energy management model focusing on economic and environmental factors to address this research gap. Figure 9 illustrates the sequential flowchart of this cooperative strategy. Furthermore, the detailed methodology encompassing mathematical models of the strategy, the validation process, and simulation results can be found in [16]. It is worth mentioning that, to cope with uncertainties, Monte Carlo simulation (MCS) and the k-means clustering algorithm are employed to prepare a set of scenarios representing the RERs output power and electricity prices. Additionally, coalitional game theory concepts are applied to model the interactions among the formed energy community members by the EHs. Specifically, the Shapley value is utilized to redistribute coalition gains among the NEHs based on their contributions and performance, a key strength of the proposed strategy. Moreover, the proposed cooperative strategy produces optimal solutions, contrasting with Nash-equilibrium methods, which rely on equilibrium points without ensuring optimality.

### *Perspectives*

The proposed cooperative energy management strategy addresses existing research gaps in the literature by introducing a novel stochastic clustering-based approach for a community of EHs. Considering a collaborative scheme and cooperation among the EHs through the formation of coalitions, specifically sharing facilities and resources, the objective of the strategy is defined as collectively reducing their total operational costs. Also, by exploiting coalitional game theory approaches, the Shapley value method is employed to fairly allocate the operation cost among the EHs, considering their marginal contributions. Also, to address uncertainties stemming from variables such as PV power output and electricity prices, a cluster-based approach utilizing the k-means algorithm is adopted. Furthermore, the proposed strategy incorporates the role of energy storage systems and demand response programs in EHs' operations. The conducted simulations have revealed the validity and effectiveness of the proposed cooperative strategy by examining comparative case studies and various operational schemes (autonomous and collaborative). Therefore, the proposed strategy appears poised to empower participating NZEBs, as an energy hub, to engage as proactive members within energy communities, such as NEHs. This arrangement not only ensures cost-effective fulfilment of their energy needs but also contributes to a substantial reduction in carbon emissions, aligning with sustainability objectives. Detailed information on simulation results are available here [16].

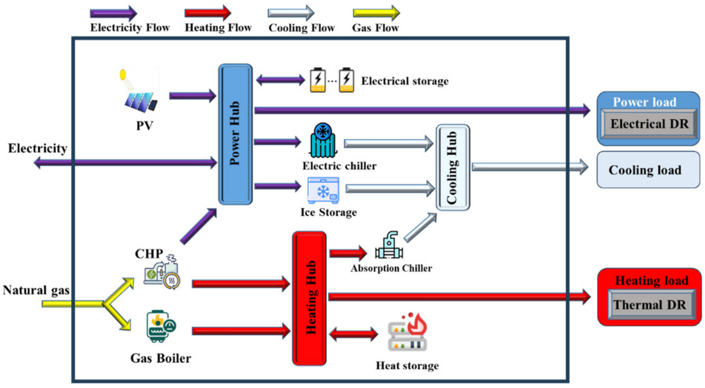

Figure 8. The configuration of the proposed EHs.

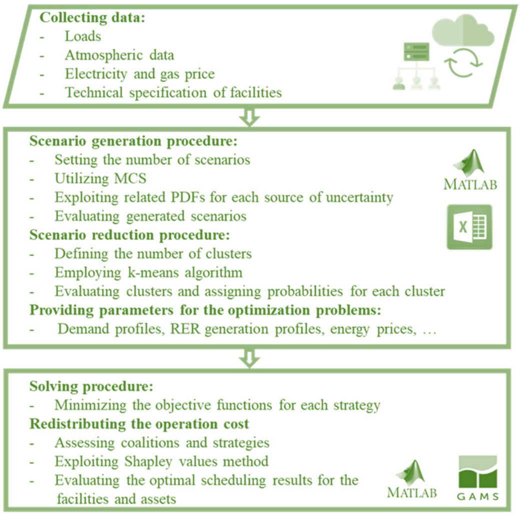

Figure 9. The flowchart outlining the proposed model for energy management [16].

### 3.2.2. Exploring the capacity for residential load adaptability: a method for evaluating operational flexibility

This subsection introduces the second-developed strategy for the operation of NZEBs. Through a review of literature, a research gap has been identified concerning the characterization and quantification of energy flexibility. Characterizing and quantifying energy flexibility in NZEBs is vital for several reasons. To begin, recognizing this flexibility enables NZEBS to efficiently adjust their energy usage in response to factors such as climate, user requirements, and grid demands. This adaptability contributes to broader energy management goals such as demand-side management and load control. Furthermore, energy flexibility is critical for NZEBS to meet the European Commission's strict requirements for NZEBs. These criteria require high energy efficiency and a strong reliance on renewable energy sources. Energy flexibility enhances the integration of renewables, ensuring optimal use of available renewable energy production. Furthermore, using energy flexibility allows NZEBS to become active participants in power markets, providing their flexibility as a valuable service via aggregators or Energy Communities (EC) managers. In the case of a single building, energy flexibility may seem to be limited. Combined with energy communities or aggregators, the aggregate potential can become significant, enabling significant energy usage adjustments as well as grid services such as demand response and balancing. Thus, while individual buildings could have limited flexibility, the flexibility of several buildings within communities or aggregators could be considerably more impactful. This not only improves NZEBs' financial viability but also helps to maintain the grid's stability and reliability. In essence, identifying and quantifying energy flexibility in NZEBS is critical to optimizing their contribution to sustainable energy ecosystems. It enables these buildings to effectively monitor energy use, incorporate renewables, and actively engage in power markets, thus driving progress toward a more resilient and sustainable energy future.

Also, it's crucial to assess building flexibility capacities before utilizing the energy flexibility it offers. There are two reasons why this is crucial. First, before powering on a scheduled appliance, the building energy management system that governs its operation should assess its flexibility. This evaluation will not only determine their availability but also make it possible to perform the cost-benefit analysis. Second, in evaluating the building that complied with their needs for flexibility, system operators ought to consider how adaptable it is. A schematic of a building, comprising several blocks, and its daily demand profiles are displayed in Figure 10.

To address the mentioned research gap, a novel methodology for managing energy flow within residential buildings to schedule shiftable appliances and energy storage has been developed. This methodology explores distinct consumption strategies and introduces novel flexibility indicators to quantify the energy flexibility potential of buildings across various operational scenarios. The detailed methodology encompassing mathematical models of the indicators, the validation process, and simulation results can be found in [17]. A summary of the proposed framework is depicted in Figure 11.

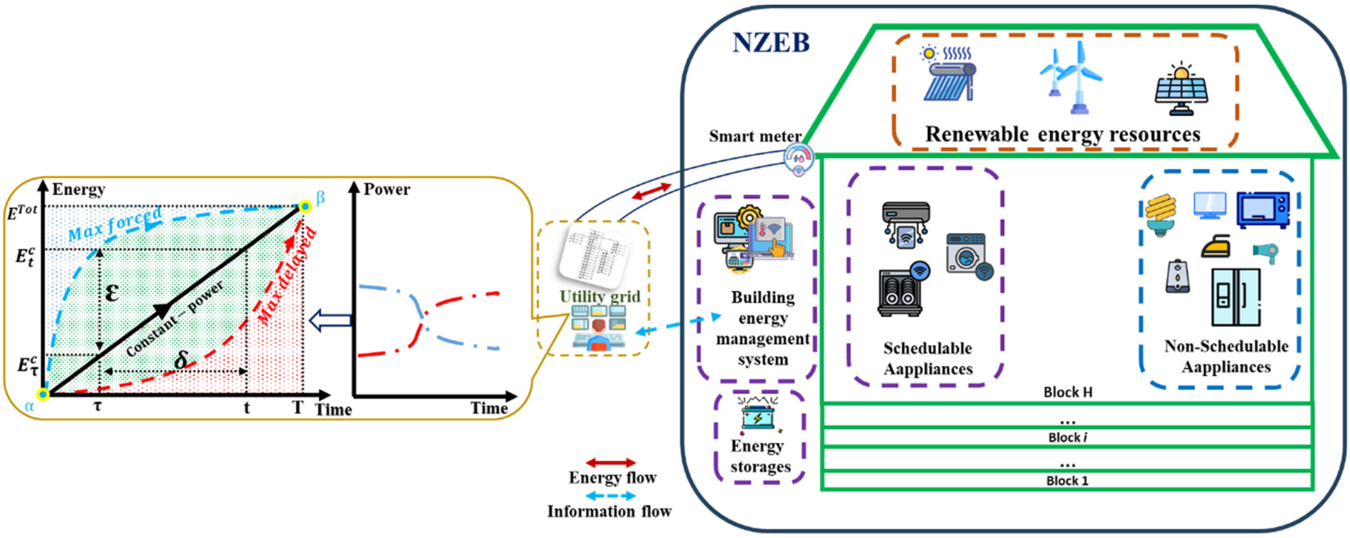

Figure 10. Energy-time profiles of a typical NZEB.

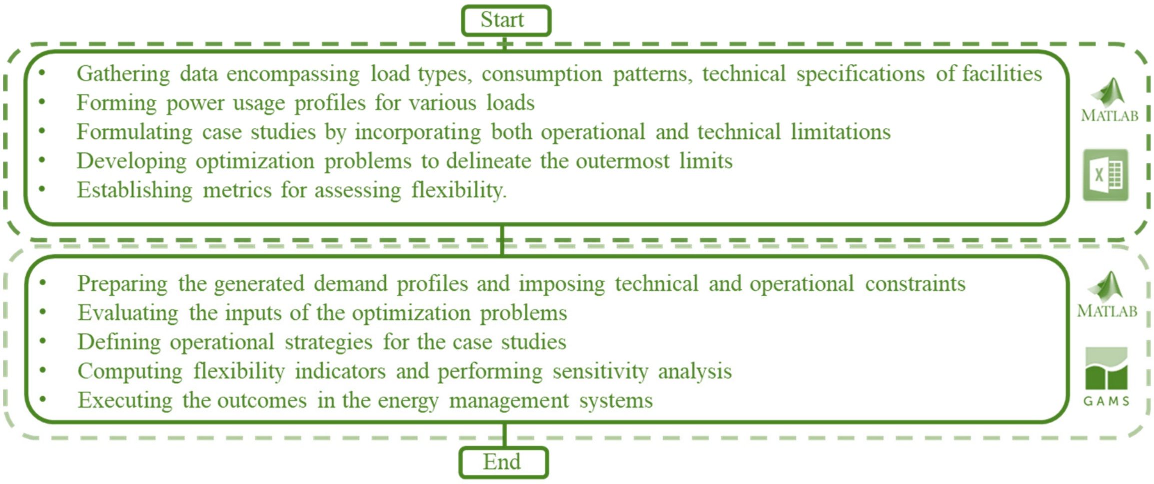

Figure 11. The schematic diagram illustrating the proposed methodology steps [17].

*Perspectives*

Characterizing and measuring energy flexibility in NZEBs is essential, especially for energy exchanges. While metrics such as time, power, and energy can individually quantify flexibility, a combined approach offers a more accurate assessment. The proposed methodology aims to evaluate NZEBs' energy flexibility through an integrated approach, analyzing the characteristics of energy curves. Understanding these curves provides valuable insights into consumer behavior and operational conditions. Additionally, analyzing these curves while considering energy flow restrictions reveals significant correlations with energy flexibility. NZEBs can enhance their adaptability and operation by managing their energy exchange with utility grids. Simulation results validate the accuracy of the proposed methodology across various operational scenarios in assessing NZEB flexibility. Detailed results are available here [17].

## 3.3. Contribution to the WP objectives

WP5 is dedicated to facilitating and coordinating research and the application of business models within collaborative renewable energy systems, microgrids, and energy management. Its primary goal is to showcase the advantages of technologies developed in WP2, WP3, and WP4 by devising cohesive strategies and offering policy recommendations aimed at transforming energy systems. This document contains an extensive report focusing on the "Development of Sustainable Strategies for Net Zero Energy Buildings and Energy Awareness using Smart Appliances" under Task 5.1.

The report begins by examining recent advancements in sustainable methodologies applicable to NZEBs, covering passive and active techniques, and the integration of renewable energy sources. Furthermore, two strategies have been developed by ESR-12 aiming to facilitate the interactions between NZEBs and the utility grids considering techno-economical aspects. Also, these strategies have been formulated and verified through optimization-based models and simulations. One notable strategy is conceptualized within the Networked Energy Hubs paradigm, fostering a cooperative framework for forming energy communities. Additionally, addressing the challenge of energy grid resilience, particularly with the rise of renewable energy deployment and interactive prosumers like NZEBs, another strategy aims to quantify energy flexibility to facilitate interactions between NZEBs and power grids.

These developed strategies for NZEBs contribute significantly to the goals outlined in WP5. Firstly, by supporting and advancing synergies between WP2, WP3, and WP4, sustainable strategies for NZEBs facilitate cooperative and distributed renewable generation systems, microgrids, and energy management systems. These strategies align with the objectives of WP5 by promoting the integration of NZEBs into a broader framework of renewable energy generation and consumption control systems. Secondly, by taking into account the comprehensive structure of smart grids, which encompasses both hardware and software components, the implementation of the developed strategies efficiently leverages the advantages offered by systems and technologies developed in WP2, WP3, and WP4. By showcasing the effectiveness of NZEBs in reducing energy consumption, utilizing renewable energy sources, and contributing to grid stability, these strategies serve as practical demonstrations of the research outcomes from other work packages. Lastly, sustainable strategies for NZEBs provide valuable insights and recommendations for policymakers to guide the transition of the energy system towards greater sustainability. By highlighting the potential of NZEBs to reduce carbon emissions, enhance energy efficiency, and promote renewable energy integration, these strategies inform policy decisions aimed at accelerating the adoption of sustainable energy practices. Overall, the development of sustainable strategies for NZEBs plays a pivotal role in advancing the objectives of WP5 and contributing to the broader goal of fostering a sustainable energy transition.

Furthermore, given the emphasis of WP5 on Green Economy Models and Management Systems, particularly in the establishment of Smart Collaborative Grids to integrate various sectors within the energy system, the developed strategies contribute to the creation of innovative, competitive, and sustainable business models in which NZEBs could participate actively in the local energy markets as well as efficiently exchange energy with the utility grids.

# 4. Conclusions

This document reports on recent advancements in sustainable strategies for Net Zero Energy Buildings. To cover this, firstly, a survey has been conducted on the related literature. Through comprehensive analysis, key areas of investigation, such as collaborative energy ecosystems within energy communities and user-centric approaches to enhance energy awareness, were identified and explored. Secondly, several strategies and frameworks have been developed aiming to contribute to the related literature. The developed strategies, including a novel cooperative energy management strategy and a methodology for assessing operational flexibility within NZEBs, demonstrate meaningful progress in addressing the identified research gaps. Additionally, the examination of optimization methodologies and modelling techniques has laid the groundwork for future research endeavours in energy management strategies for NZEBs and energy communities. The outcomes of IRP-12 have been disseminated through various scientific publications, including papers in the *International Journal of Electrical Power & Energy Systems* and conference submissions. Furthermore, the development and validation of simulation frameworks aligned with the proposed strategies showcase the potential efficacy of these approaches in facilitating the deployment and operation of NZEBs within energy communities. Moving forward, the integration of renewable energy resources and the incorporation of interactive interfaces aim to enable NZEBs as active participants in power markets, contributing to economic benefits and sustainable cooperation within energy communities. Through these efforts, ESR-12's contributions to WP5 have paved the way for the implementation of optimal energy management strategies for NZEBs, driving progress toward a greener and more sustainable energy future.

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