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Review

Autonomous Cyber-Physical Systems Enabling Smart Positive Energy Districts

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Abstract

The European Union (EU) is striving to achieve its goal of being climate-neutral by 2050. Aligned with the European Green Deal and in search of means to decarbonize its urban environments, the EU advocates for smart positive energy districts (PEDs). PEDs contribute to the United Nations' (UN) sustainable development goals (SDGs) of "Sustainable Cities and Communities", "Affordable and Clean Energy", and "Climate Action". PEDs are urban neighborhoods that generate renewable energy to a higher extent than they consume, mainly through the utilization of innovative technologies and renewable energy sources. In accordance with the EU 2050 aim, the PED concept is attracting growing research interest. PEDs can transform existing energy systems and aid in achieving carbon neutrality and sustainable urban development. PED is a novel concept and its implementation is challenging. This study aims to present the emerging technologies enabling the proliferation of PEDs by identifying the main challenges and potential solutions to effective adoption and implementation of PEDs. This paper examines the importance and utilization of cyber-physical systems (CPSs), digital twins (DTs), artificial intelligence (AI), the Internet of Things (IoT), edge computing, and blockchain technologies, which are all fundamental to the creation of PEDs for enhancing energy efficiency, sustainable energy, and user engagement. These systems combine physical infrastructure with digital technologies to create intelligent and autonomous systems to optimize energy production, distribution, and consumption, thus positively contributing to achieving smart and sustainable development.

Keywords: positive energy districts; PED; internet of things; IoT; smart cities; cyber-physical systems; artificial intelligence; AI; blockchain; energy efficiency; smart districts; review

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1. Introduction

One of the European Union's (EU) primary objectives in addressing global warming is to become the world's first climate-neutral continent by 2050. As is outlined in the European Green Deal, this goal involves measures to decrease greenhouse gas (GHG) emissions, increase renewable energy use, and improve energy efficiency [1]. Challenges include the need for further policy changes and reliance on the capabilities of diverse member states.

The energy systems of buildings are important for realizing net zero emissions, and achieving this goal has prompted contemporary advancements in intelligent buildings, intelligent cities, and intelligent regions. Urban areas are responsible for utilizing approximately 65–70% of global energy and producing 70–75% of global GHG emissions [2]. Hence, European cities are increasingly encouraged to mitigate building and urban infrastructure emissions. Buildings together with transport are responsible for more than 70% of global energy consumption and at present only 20% is supplied by renewable energy sources [3]. As a result, buildings and electric vehicles have considerable potential to enable the optimization and balance of energy supply and demand.

Distributed energy generation is rapidly growing through the utilization of Renewable Energy Sources (RESs) for both cooling and heating, as well as through their integration into electric vehicle charging infrastructure. The production of renewable energy is affected by various meteorological factors, including wind speed, cloud cover, temperature, and precipitation [4].

The enhancement in the utilization of RESs, prosumer engagement, Distributed Energy Resources (DERs), and smart grids has created new challenges regarding the energy supply balance, complexity, and stability of the overall energy system [5]. DERs represent small-scale energy systems that supply power to a neighboring location. Following the initial initiative in 2008, the Strategic Energy Technology (SET) Plan, revised in 2015, was adopted by the EU to create effective energy technology policies for Europe [6]. The aims were to speed up knowledge creation, technology transfer, and knowledge uptake to achieve energy transition, address climate change, and achieve the sustainable development goals. The SET Plan includes ten key action areas. In this context, action 3.2, "*Smart Cities and Communities*", was established to support the design, planning, organization, implementation, and replication of "100 Positive Energy Districts" (PEDs) by 2025, as part of broader actions and efforts to promote greener initiatives and sustainable urban development [6]. The PED stores the surplus energy produced by RESs or exports it to the overlapped grid and, when there is a shortage at the local level, it buys energy from the grid [5]. A definition of a PED is as follows: "*Positive Energy Districts are energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and 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*" [7]. At the district level, earlier ideas of Nearly/Net/Positive Zero Energy Buildings (ZEBs) were extended with energy generation, consumption, and storage interoperability and interaction [8]. Results and data from existing PED approaches across Europe have been collected by JPI Urban Europe [9,10].

Being energy-efficient and energy-flexible, PEDs require the integration of different energy systems (electricity, heat, cooling, energy storage) as well as interaction between regional, building, and user energy; information and communication technologies (ICT); transport; and cyber-physical systems (CPS). Energy-positive areas can be of many types and consist of many different actors.

Saheb et al. [11] revealed findings from 62 pioneering PEDs that had either a zero-carbon or zero-energy goal. Four PEDs were analyzed in depth. They emphasized that "*from a policy perspective, the concept of a zero-energy community has proven to be hard to implement and evaluate*", despite the fact that there is evidence for "*the feasibility of the zero-energy concept for individual buildings*" [11]. They identified four factors that are crucial for successful implementation [11]:

(i) "*Measurable targets and a clear implementation timeline*";

(ii) *"Transparency about progress towards these targets and any revisions or trade-offs made during project implementation"*;
(iii) *"The supply and demand of urban services (energy, waste, water and transport) needs to achieve some integration at a local level"*;
(iv) *"The local residents and community need to be meaningfully engaged"*.

The four projects followed different approaches for their PED implementation.

The majority (66%) of existing PED projects attach newly built neighborhoods to existing ones [9]. The complexity of a PED project requires that all stakeholders are involved in the project from the very beginning and demonstrate consensus about undertakings. Technological limitations, complex ownership structures, building protections, and preservation of the cityscape are significant PED implementation challenges. It is important to note that "*approximately 75% of the buildings in the EU are energy inefficient*" [12]. Hence, the integration of PED solutions to the existing urban infrastructure is a priority. Terés-Zubiaga et al. [13] emphasized that an effective way to accelerate energy consumption reduction in buildings is to increase renovation rates at a district scale. The Annex 75 project [13,14] of the "International Energy Agency Energy in Building and Community" created a methodology for "*investigating the cost-effective balance between carrying out energy efficiency measures and deploying measures for renewable energy sources regarding the renovation of buildings at district level*". Success stories, lessons learnt, good practice, and policy guidelines from the Annex 75 project have been published in [15].

The JRC report [16] highlights that reduction of carbon footprints and the empowerment of citizens and stakeholders to take a lead in their own communities are the main benefits of PEDs. The report also emphasizes that the PED approach is complex because of many technologically innovative combinations on a district level, such as flexible grid usage, demand-side actions application, and photovoltaic–thermal (PVT) systems [17]. For the creation of smart systems and for addressing management issues, including monitoring, control, and energy generation optimization, consumption, and trading, ICT as well as Autonomous CPSs need to be used [18]. CPSs facilitate constant communication and data analysis shared between infrastructures, cyber platforms, and physical devices. Hence, multiple synchronous applications over diverse network structures are utilized. Thanks to the continuous technological developments in the domains of electronics, robotics, and computer science, automated and intelligent sensing systems with improved performance are being developed. CPSs are increasingly being utilized to create different intelligent applications, including smart cities, grids, buildings, cities, transportation, and utility systems.

The European perception of smart cities highlights sustainable urban environments that use smart technologies with information and data collected through sensors from the vicinity. Artificial intelligence (AI) is basically integrated into smart innovative technologies which assist end-users in comprehending their energy usage. ZEBs attempt to reduce energy consumption by capitalizing on local energy production and ensuring that the produced energy does not exceed the energy consumed by the buildings [19]. Nowadays, urban development is advancing from individualized building solutions to whole-district solutions [20] or Energy Communities (ECs) [21]. These solutions were introduced in 2019 in EU legislation. The aim of ECs was to empower citizens to propel the energy transition locally so that they could benefit from the advantages, such as improved energy efficiency, lessened energy poverty, reduced energy bills, and the potential for local green jobs [9]. The thought behind ECs was to improve public acceptance of renewable energy approaches and to attract private investment. A political objective of achieving one EC by 2025 per municipality with a population of higher than 10,000 was proposed [22]. The ECs are significantly correlated with PEDs.

The transactive energy market aims to enhance power systems' efficiency, robustness, and reliability by working towards a more intelligent and interactive future for the energy industry. Industry 4.0 technologies, comprising CPSs, Digital Twins (DTs), and the Internet of Things (IoT), are being used to introduce intelligence in the manufacturing industry [23]. Additionally, the Industry 4.0 paradigm is based on four strategic principles related to CPSs, as follows [24]:

1. *Interconnectivity*: devices, machines, sensors, and humans communicate among themselves through the IoT;
2. *Technological Assistance*: the technological systems support humans in monitoring, problem-solving, and decision-making;
3. *Information Transparency*: operators receive detailed information that is critical for decision-making;
4. *Decentralized Decision-Making*: CPSs take decisions and perform tasks independently and automatically.

The concept of Construction 4.0, a term used for making use of digital advancements in the construction industry, employs similar principles to Industry 4.0 [25]. In Construction 4.0, data-driven systems are utilized for management of physical processes and for the decentralization of processes associated with decision-making [25]. The emphasis of this study is on the role of CPSs in PEDs. CPSs are traditionally leveraged in large-scale industrial and autonomous domains [26]. However, with recent technological developments, new application domains are available for CPSs, including applications for smart grids, electric vehicles, PEDs, etc. A significant research gap in the context of CPSs within PEDs lies in the absence of a comprehensive approach to assessing and modeling the complex interactions between physical components on one hand and cyber components on the other hand. The potential of CPSs to optimize energy management and enhance PED sustainability is recognized. However, description and examples of their practical implementation, particularly in the context of urban energy systems, is scarce in the literature. This entails a need for detailed description of CPS architectures tailored to PEDs, and strategies for integrating CPSs into existing infrastructures, ensuring compatibility and interoperability between new and legacy systems. The interplay between buildings, infrastructure, and user behavior needs to be taken into consideration, together with integration of heating, cooling, electricity, etc. Engaging stakeholders, such as citizens, policymakers, and energy providers in the design and implementation of CPSs is a significant challenge. Lately, a more interdisciplinary approach, including a connection between human factors and the CPS domains, has been identified and is called "*human-in-the-loop CPS (HilCPS)*" [27]. Nevertheless, current research usually focuses on specific aspects of CPSs in PEDs, such as energy management and cybersecurity. A holistic approach is needed to integrate knowhow and experience from different fields, including computer science, energy engineering, urban planning, and social sciences.

The aim of this study is to examine the role of contemporary emerging technologies, including CPSs, DTs, AI, IoT, edge computing, and blockchain, in the creation, advancement, and operation of PEDs. The main research question (RQ) of this study is, "If and how do emerging technologies, such as CPSs, DTs, AI, IoT, edge computing, and blockchain, affect PEDs?".

The study adopted an interdisciplinary approach to broaden the technological viewpoint and concentrated on the benefits and challenges these technologies bring to PEDs. This study contributes to the understanding of the concept of the PED, as well as of the success factors, barriers, and interdependencies of PEDs. Specifically, the study contributes to the existing body of knowledge by providing a comprehensive, broadened view of emerging technologies and their role in and impact on PEDs. By examining the practical

PED applications presented for emerging technologies, which were identified as key to the successful deployment of PEDs, and their relationship, this study aims to improve our understanding of the complex interrelations between them and their impact on PEDs.

This paper is organized as follows: Section 2 describes the research method, while Section 3 analyzes and presents the emerging technologies that enable PEDs, including CPSs, DTs, AI, IoT, edge computing, and blockchain technologies. Section 4 describes the challenges and potential solutions in utilizing these technologies in PEDs, focusing on both business model challenges and technological challenges. Section 5 presents the relationships between these technologies and their influence on PEDs. Finally, the outcomes are further discussed in Section 6 and concluding remarks and suggestions for future work are presented in Section 7.

2. Method

The explanatory research approach is used to understand underlying processes, explore cause-and-effect relationships, and explain phenomena in greater depth, e.g., a multidisciplinary approach of emerging technologies. It helps researchers gain insights, identify patterns, generate hypotheses, or clarify concepts before conducting more structured, conclusive research. A literature review is a common explanatory research method for reviewing existing information to identify gaps or trends, seek new insights, and assess phenomena from a different viewpoint.

This study applies an explanatory research approach by exploring why something happens (the role of CPSs in PEDs), explaining causes (what are the technological developments suitable for utilization in PEDs), and consequences (how do CPSs and new related technological developments support PEDs). Therefore, to provide an overview of autonomous CPSs, DTs, AI, IoT, edge computing, and blockchain technologies and their use in smart PEDs, various databases were examined to identify relevant documents that had previously been published in high-level academic journals and conference proceedings.

Although systematic literature reviews are believed to be an accurate approach for gathering articles, it is not a suitable approach for addressing broad topics that necessitate comprehensive collection of data [28]. Since the scope of this study is wide-ranging, a critical literature review approach was used by methodically searching for suitable earlier research that highlighted how emerging technologies are utilized in PEDs. Two comprehensive critical literature review search approaches were used to identify suitable narratives:

(i) Articles and databases reporting on a variety of PED projects; PED studies and reports from the EU SCM platform [29] and the JPI Urban Europe "*Booklet of Positive Energy Districts in Europe*" [10] were used to identify PEDs that utilize and report on the integration of contemporary technologies. These studies and reports mainly refer to the PED perspective from a multidisciplinary viewpoint, based on the technologies and lessons learnt from experiences on European level. "*Even if these works are very relevant for mapping PED and for the creation of a structured repository of information, they do not fully address the complex set of urban challenges and the objective to support decision making, the implementation and replication of PEDs in municipalities, nor the creation of capacity and community building to drive urban transformations*" [30]. The interactive PED-EU-NET [29] database, which provides an overview of diverse PED projects, was also used to identify suitable PEDs for this study.

(ii) Scientific articles in acknowledged library repositories and scientific databases, including "Web of Science", "Scopus", "ACM", "IEEE", and "Google Scholar". Based on the guidelines of Jesson and Lacey [31], specific keywords like "cyber-physical systems", "CPS", "artificial intelligence", "AI", "automation", "sensors", "robotics", "internet of things", "IoT", "edge computing", "smart positive energy districts", and "PED" were used to identify relevant documents in a non-systematic way. The selected keywords guided the identification of relevant articles that focus on recent technologies that contribute to successful PED implementation.

The two comprehensive critical literature review search approaches were used with the aim of identifying, categorizing, evaluating, and presenting earlier research. Therefore, taking into consideration that the goal of this study is to provide an overview of the different PED aspects related to emerging technologies, a critical/integrative literature review approach was followed. Hence, this study contributes to the existing literature by expanding our current understanding of PEDs and of the related technologies that support their realization, as well as by highlighting future research and development in this domain.

3. Emerging Technologies Enabling Positive Energy Districts

The technologies utilized in PEDs can be divided in three categories [14]:

- Demand reduction/energy-saving technologies implemented at the individual building level;
- Energy distribution and supply systems implemented at both individual building and urban scale;
- Energy storage systems implemented at both individual building and urban scale.

CPSs also emphasize human interaction. Nonetheless, most energy-saving approaches have been found to lack consumer appeal [5]. Having real-time information system at district level will motivate citizens to save energy through state-of-the-art local community perception. Advanced contemporary technologies, like IoT, AI, digital twins, edge computing, blockchain, and 5G networks are critical to future energy systems as they facilitate predictive analytics, smart grids, and DERs. Below, emerging technologies that have been found to have an impact on PEDs are discussed.

3.1. Cyber-Physical Systems

CPSs are essential to develop smart PEDs and support the production of sustainable and efficient urban environments. CPSs are important for enabling, managing, and optimizing PEDs. CPSs are "*complex multi-layered feedback systems that combine computing resources and interaction with the physical environment using sensors and actuators*" [32]. By integrating physical energy infrastructures with digital calculations, real-time control of distributed energy, and storage and communication, CPSs enable (i) monitoring, detection, and mitigation of disturbances; (ii) efficient and resilient operation of energy systems at the district level; and (iii) defense against cyber-attacks, secure state estimation, and control. They also stimulate stakeholder participation (a fundamental feature of successful PEDs) through their data sharing platforms for data sharing and community participation. CPSs in energy are applied in areas such as smart grids, renewable energy integration, microgrid control, energy storage management, and efficient power system operation, enhancing efficiency, reliability, and sustainability. CPSs contribute to energy-aware environments through the integration of energy consumption data into software development processes [32].

CPSs combine complex physical network systems and cyber systems to optimize energy utilization and to enhance the functionality of smart grids and urban infrastructures. Recent developments in information and ICT and embedded system design have enabled the adoption of CPSs in practical applications. An example is the change of traditional energy grids into smart grids which utilize "*a two-way communication system for information transformation, power generation, and distribution*" [33], via the use of real-time advanced monitoring, communication, and control systems. Hence, CPSs support smart grid technologies, facilitating advanced energy management, microgrid control, and protection, which are crucial for PEDs to operate efficiently and sustainably [33]. A specific case study, namely the Aspen Smart City project in Vienna, Austria [34], can be mentioned, due to the use of CPSs to link monitoring in real time, intelligent control, and decision-making for optimizing energy performance. CPSs enable PED outcomes via demand response (consumption shift during peak hours or low renewable generation), real-time optimization (reducing energy losses by controlling when to consume, store, or feed energy back to the grid), user interaction (residents access dashboards to monitor usage and receive suggestions regarding how to reduce consumption), and fault detection and maintenance (detection of equipment performance irregularities activates alerts or maintenance requests). CPSs used in the Aspen project include the following:

(i) *Building Energy Management Systems (BEMS*) connected via CPSs to manage heating, cooling, and lighting according to real-time data, and to optimize energy use by adaptive control while comfort levels are maintained.
(ii) *Smart meters and IoT sensors* that collect environmental data, such as temperature, humidity, and occupancy, and monitor energy generation and consumption in real time across buildings.
(iii) *Renewable Energy Integration Platforms* managing energy flows dynamically depending on demand and supply. A central CPS is used to collect data from solar PV panels on rooftops.
(iv) *Smart Grids and Decentralized Energy Storage* (e.g., batteries) are managed by CPSs to store excess energy (e.g., solar power). Demand is estimated by predictive algorithms and grid behavior is adjusted accordingly.
(v) *Digital Twins* are used as virtual models of the physical district to simulate scenarios for energy optimization. CPSs enable real-time feedback loops to update the digital twin with live data.

Smart grids utilize advanced ICT to deliver reliable, robust, and secure energy; improve energy generation; and increase operation and process efficiency, transmission, and distribution through interconnected smart meters and multidirectional information flows. Such systems improve operational efficiency and offer flexible choices for energy prosumers [35]. CPSs can detect new safety weaknesses, but also offer tools regarding advanced and early threat detection, risk assessment, and mitigation of disruptions, thus ensuring a reliable energy supply, which is of utmost importance for safeguarding PED operations against cyber threats.

Based on the smart grid structure presented in Yu and Xue [35], it can be inferred that many stakeholders exist within highly networked and large-scale systems. CPSs bring significant benefits to energy management by integrating computational and physical processes to enhance reliability, efficiency, and sustainability. CPS frameworks allow full utilization of renewable energy sources. This can be attained by optimizing energy use and by integrating renewable energy into energy management systems. Smart grids are increasingly being applied across various domains including industry (cleaner production strategies, reduced energy consumption, and improved material utilization), residential customers (optimized energy use, occupancy detection, and prediction) and commercial customers (flexible loads). CPSs are defined "*as transformative technologies that can seamlessly connect the physical world with the virtual world through their advanced and novel technologies*" [36]. They are a significant element of the information age. Recent developments in technical and organizational interoperability of building data have enabled pertinent innovation regarding energy optimization and energy delivery. Innovative energy optimization methods utilize technologies such as the IoT and CPSs to reduce energy consumption [25]. Additionally, Yu and Xue [35] highlight the central role of smart grids and present key entities that are connected to smart grids, including conventional power plants (nuclear and thermal plants), consumers (commercial, residential, industry), communication, renewable energy (wind farm, solar panel, hydro power), storage, microgrids, and electric vehicles. Regarding smart grids, operations and control are spread across the entire power system to enable bi-directional power flows. The flexibility, portability, safety, and security needs of energy supply necessitate interaction between the power networks, the cyber systems, and the users.

3.2. Digital Twins

A DT "*integrates the IoT, AI, machine learning, and analytics, to create living digital simulation models that update and change information as needed*" [20]. Therefore, a DT constitutes a model that "*continuously learns and updates itself from multiple sources to represent its near real-time status*" [20]. Additionally, a DT is a combined approach involving "*new types of analysis and modelling based on big data and machine learning/artificial intelligence, which combines capacities of virtual model, data management, analytics, simulation, system controls, visualization and information sharing*" [37]. DTs are considered to be a significant solution for designing and optimizing PEDs [20,37]. This is because virtual modeling, analysis, and testing of buildings and districts before they are built is regarded as more resilient and more efficient, due to the fact that it enables real-time and predictive monitoring, simulation, and stakeholder collaboration. Therefore, through the continuous tracking of energy consumption, production, and storage, DTs facilitate proactive management and optimization of energy systems within districts. Effectively collecting and managing data from building information models (BIM), IoT devices, and sensors is essential to optimize energy flows, support participatory planning, and ensure sustainability in PEDs. DTs are created by using pioneering simulation models that integrate real-time data from diverse sources regarding real-time states (e.g., moisture, occupancy, energy consumption, temperature, CO^2 concentration, renewable production, etc.). Furthermore, DTs continuously learn and renew themselves from multiple sources and, as a result, can support the identification of diverse energy strategies (e.g., identifying the most effective way to achieve a positive energy balance).

DTs are significant for achieving the aims of PEDs in terms of raising the threshold of self-produced energy, energy surplus, and climate neutrality. This is achieved through real-time energy management and collaborative planning for sustainability. Their continuous development and integration will be crucial to the successful transition to energy-positive urban environments. DTs can be used for energy supply and demand measures, carbon emissions, indoor air quality, and thermal comfort. They can also be applied to calculate the expenses for building operation, maintenance, renovation, replacement, and the payback periods of energy-saving measures. In their work, Zhang et al. [20] present the key components of a digital PED twin, as can be seen in Figure 1. In addition, they revealed that the energy data in a digital PED twin (aggregated through the whole life cycle) is collected and transported by diverse sensors and IoT networks from the operational data network to a data analytic center, where data is either sent to stakeholders for decision-making, or returned to the individual systems for regular operations. The different decisions that stakeholders take rely on advanced analytics that are actuated in an automated infinite-state mode of operation. The digital PED twin increases system resilience by considering interdependent systems and optimizing future decisions and operations. The DT environment enables collaboration, communication, and interaction between all stakeholders involved in the life cycle of PEDs. The flexibility and robustness of the system increase during operation due to the reliance on real data.

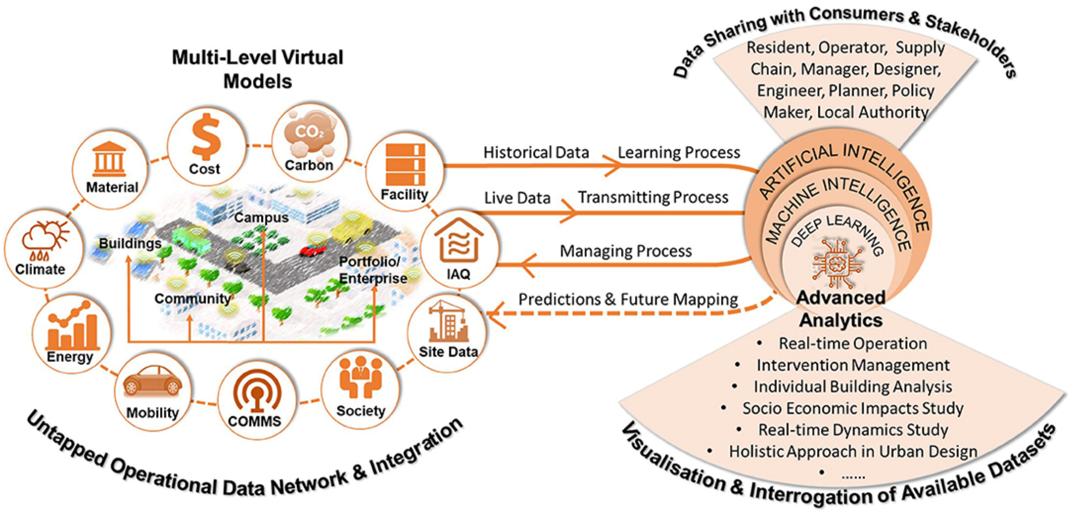

Figure 1. Key components in a digital PED twin [20].

Creating city and district DTs signifies a radical shift toward urban sustainability from design to construction and maintenance based on the Industry 4.0 and Construction 4.0 principles [25]. DTs utilized in PED energy management comprise diverse energy system optimization, predictive analytics, and real-time monitoring. After using DTs in two urban initiatives, Tartia and Hämäläinen claimed that the benefits of using urban digital twin include "*visualization, planning, and facilitating dialogue among various stakeholders*" [38]. DTs enable the optimization and automation of energy management in PEDs, reaching the goals of ZEB requirements.

DT ecosystems are associated with three main entities, namely (i) a physical object, (ii) its virtual duplication, and (iii) the connection of the physical object and its virtual duplication. Such DTs reduce lifecycle management for storing, managing, and processing big data regarding the urban environment. Digital PED twins can also be classified into three distinct levels, namely (i) an improved version of the BIM model, (ii) platforms of semantic data flows, and (iii) analysis and feedback of big data [20]. Practical application cases for DTs in PEDs include the following:

(i) *Energy Flow Optimization:* Simulation and optimization of the energy flows within a district with a DT, through modeling of energy generation, energy consumption, and energy storage.
(ii) *Demand Response and Load Shifting:* DT forecasts energy demand and supply and thus enables dynamic demand response programs to reduce peak loads, avoid fossil fuel-based grid reliance, and improve grid stability.
(iii) *Renewable Energy Integration:* DT evaluates where and how to deploy renewable energy most effectively, considering local climate and urban structure; hence, optimal operation of distributed energy resources is obtained for maximum energy production and minimum losses.
(iv) *Integration with Smart Grids and Utilization:* DT acts as a virtual control center that balances energy inflows/outflows and interacts with utility signals for bi-directional energy trading and integration into larger energy networks.
(v) *Battery and Thermal Storage Management:* DT predicts energy needs and storage behavior to schedule charging/discharging.
(vi) *Carbon Emissions Tracking and Mitigation:* DT quantifies carbon footprint from building operations, transport, and energy use by supporting strategies to meet EU, national, and local-level carbon neutrality targets.

(vii) *Urban Planning and Retrofitting:* DT simulates the effects of insulation, window upgrades, passive solar design, and HVAC improvements for providing cost-effective design choices.

(viii) *Citizen Engagement and Behavior Modeling:* DT models human behavior, such as thermostat settings, and provides feedback via apps or dashboards to promote energy-saving behaviors and increases public engagement in sustainability goals.

(ix) *Predictive Maintenance of Infrastructure:* DT detects anomalies in system performance and predicts maintenance needs for preventing downtime, increasing energy efficiency, and reducing operational.

The DigiTwins4PEDs project (2023–2026) is a PED which focuses on living labs in Stuttgart (Germany), Vienna (Austria), Rotterdam (the Netherlands), and Wroclaw (Poland) and integrates urban digital twins into processes of public participation. The project aims to apply the urban DT framework to simulate, model, and visualize the PED and to empower the local community to engage in PED co-creation together with city representatives. The living labs operate as mediators among stakeholders for the evaluation of the potential of using urban digital twins as a collaborative tool for PED co-creation [39]. Similarly, the DT4PEDs project utilizes digital twins in new construction and retrofitting across Austria, Sweden, and Turkey. It uses living labs for energy information flows, stakeholder dialogue, and quality assurance throughout the PED development process [40]. A digital twin combined with the IoT and AI was used in Rome for simulation of and optimization of energy interventions in a PED with 16 buildings, including 216 apartments. The results showed improvements in renewable energy integration and progress toward near-zero energy building standards [25].

3.3. Artificial Intelligence

The use of AI for urban planning is an understudied research area [41]. AI facilitates smarter planning, operation, and management of PEDs. Using AI technologies, big data, and urban intelligent systems is vital to develop intelligent urban environments. The aims are to improve urban environment management and smart city quality of life [7,8]. AI models are considered to be efficient tools for treating complex and immense data. They learn relationships between a system's outputs and inputs [42]. From prediction of energy demand and generation to optimization of energy flows and load management, AI is playing a pivotal role in the transformation of energy infrastructure. For example, AI supports the organization, planning, and operation of smart grids by predicting energy demand and generation, optimizing energy flows, and coordinating energy resource distribution [43]. Through this process, the reliability and resilience of the grid is enhanced and the integration of various energy sources is improved.

In the context of energy efficiency optimization, AI can provide continuous improvements of energy-saving strategies. This is possible because of the ability of AI to dynamically adapt and learn from data [44]. AI energy efficiency optimization is based on, e.g., occupant patterns, weather conditions, and energy prices; hence, AI enables reduced energy consumption, with subsequent reduced energy costs and decreased GHGs. AI can also speed up the adoption of renewable energy sources, such as solar and wind, by improvement of forecasting, energy storage optimization, and grid stability management [43]. This results in more efficient, more robust, and more reliable use of renewable resources; hence, it supports the shift towards net-zero energy systems. The configuration and control of energy storage systems with the use of AI ensure stable and economic operation as regards renewable energy [43].

AI's ability to overcome the economic, social, environmental, and governance challenges of cities and districts is one of its main advantages. It is becoming a substantial means of realizing smart and sustainable progress [41]. AI techniques are increasingly used to analyze large amounts of data and extract important insights in PED performance [42]. Various applications, including load predictions, energy pattern profiling, regional energy consumption mapping, building stock measurement and analysis, and retrofit strategy effect analysis are successfully addressed by this kind of approach. AI algorithms can optimize energy use in buildings by analyzing occupancy patterns, weather data, and historical energy usage [45]. Heating, cooling, and lighting systems can automatically adapt in line with real-time conditions. As a result, energy savings are achieved without compromising comfort levels. Two AI techniques, machine learning (ML) and natural language processing (NLP), were examined by Han et al. [42] to understand their potential for PED element modeling, extracting, and mapping. These tools facilitate the optimization of energy flows, control systems, and design strategies through the analysis of large datasets. The outcomes result in more accurate and actionable insights into the successful planning and implementation of PEDs.

Complex environmental data used to identify patterns, predict changes, assess risks, and guide decisions can be analyzed by ML. The results revealed that both ML and NLP, by utilizing vast amounts of data, have significant potential for optimization, control, design, and stakeholder mapping. Hence, they can provide precise and valuable insights to support the planning and implementation of PEDs. AI fosters advancements in energy material and complements innovations in blockchain and the IoT [43]. Nonetheless, there remain challenges associated with the use of AI, such as ethical perspectives associated with the automation of the energy sector and autonomous decision-making, technical and economic issues (e.g., scalability, intermittency of renewable energy, and costs of infrastructure positioning), and regulatory issues associated with its application [46,47]. Other challenges include the accessibility and quality of data, system interoperability, and the complexity of energy data analysis [20,48]. Practical application cases for the use of AI in PEDs include the following:

(i) *Energy Demand Forecasting:* AI models use occupancy levels, weather data, and historical usage to forecast building energy consumption in real time using machine learning and Convolutional Neural Networks (CNNs). This enables dynamic energy balancing and reduces peak loads [49].
(ii) *Renewable Energy Optimization:* AI predicts the optimal slope and orientation of solar panels based on seasonal and daily weather patterns for increased energy production and efficiency.
(iii) *Smart Energy Management Systems (SEMS):* AI-based systems autonomously control heating, ventilation, lighting, and appliances and adapt building climate control systems accordingly by also taking occupancy predictions into consideration to minimize energy waste and maximize comfort.
(iv) *Energy Storage Management:* AI coordinates when to use stored energy versus grid electricity for cost saving and optimizes charging/discharging of batteries based on real-time supply and demand for enhanced energy reliability and cost efficiency.
(v) *Peer-to-Peer (P2P) Energy Trading:* AI algorithms facilitate decentralized energy trading among PED members. Blockchain and AI work together to enhance local energy exchange and improve grid independence. This is enabled by automating micro-transactions between households (e.g., using solar panels).
(vi) *Grid Interaction and Flexibility Services:* AI manages district-level battery storage to respond to real-time grid signals and predicts when and how much energy can be fed into or drawn from the grid. Hence, AI supports grid stability and participation in demand response programs.

(vii) *Building Information Modeling (BIM) and AI:* AI identifies energy efficiency improvements in district planning stages. AI can be used with BIM to simulate and optimize energy use in new or retrofitted buildings for improved building performance design before construction.
(viii) *Predictive Maintenance:* AI detects anomalies in energy systems (e.g., HVAC, solar inverters, etc.) by indicating performance drops in solar panels due to dirt accumulation for reduced downtime and extends equipment life.
(ix) *Mobility and Electric Vehicle (EV) Integration:* AI directs EVs to charge during solar peak hours and discharge during peak demand and optimizes EV charging schedules based on district energy supply and demand to avoid grid overloads and use surplus renewable energy.
(x) *Citizen Engagement and Behavior Change:* Personalized AI insights show how a household's actions contribute to the district energy surplus and AI-driven apps and dashboards provide feedback to enhance awareness of and engagement in achieving PED goals. For example, speech emotion recognition (SER) could be deployed to recognize occupants' emotional feelings and dynamically adjust the system accordingly [50].

3.4. Internet of Things

The IoT is an innovative and continuously growing technology consisting of a network of physical devices with embedded software and sensors that collect and share data over the Internet [51]. The IoT is crucial for the realization of PEDs as it enables real-time monitoring, control, and optimization of energy flows across infrastructures, buildings, urban districts, and mobility systems without requiring human intervention. The IoT is important for the successful implementation of PEDs, because of real-time monitoring, progressive energy management, and efficient incorporation of renewables [52]. The IoT promotes sustainability, resilience, and a surplus energy balance in PEDs by linking and optimizing various energy resources.

The development of the IoT is one of the most significant technological innovations of the 21st century. Demand for automation and efficiency has inevitably contributed to advancements in the IoT [53]. As the IoT comprises an interconnected network of diverse devices, it connects software, hardware, and physical nodes [25]. Since the IoT aims to create knowledge and enable intelligent decision-making, it focuses on collecting and exchanging data amongst diverse devices and infrastructures in real time [54]. The IoT is defined as "*a global dynamic information network that involves interconnected devices and objects and aims at the mutual interconnection and interaction among people, services and devices at any time and regardless of location*" [36]. The IoT aims at the implementation of robust, autonomous, and secure interconnections and data exchange between devices and real-world applications [55]. The IoT promotes innovations as it combines numerous technologies that empower sensors and actuators to sense and collect important information, to communicate, and to collaborate, as well as to provide smart data analysis, take decisions, and take actions. IoT technologies penetrate our daily lives by introducing new contemporary ways of interaction within smart environments through sensors, actuators, and other technological devices and embedded systems. Developments in the IoT are leading to advances in various sectors, since intelligence can be infused in devices through the use of IoT and AI technologies. In particular, IoT sensing systems have brought about several innovative applications, which, in turn, have contributed to improving efficiency, productivity, and sustainability. IoT applications in PEDs include (i) smart grid integration that provides improved grid stability and integration with renewable energy sources; (ii) energy management systems enabling optimal scheduling, forecasting, and coordination;

and (iii) E-mobility (electric vehicle) management, reducing GHG emissions and enabling efficient power usage and recharge.

IoT services are fundamental in realizing smartness in diverse urban situations. The smart grid is one of the most significant applications of the IoT [56]. In cases where availability of or trust in communication has broken, different negative outcomes may occur, including reduced national security, interruption of public order, large-scale economic damage, or even loss of life. The use of the IoT in smart buildings involves real-time environment monitoring, building access management, and district or building energy demand and consumption. Energy management involves tasks such as planning and operation of energy production and consumption, monitoring energy levels, and distribution and storage of energy. When the IoT is used in energy management, it integrates complex digital and physical components within distributed CPSs, offering improved efficiency, reduced costs, and improved utilization of resources [45]. The concept of energy-aware distributed CPSs has been introduced to account for sustainability. Traditional non-functional requirements are being extended with supplementary attributes for sustainability, such as energy consumption [32]. Hence, Ciccer et al. [32] proposed the use of "*energy-aware architectural models and edge/cloud computing technologies to design next-generation, AI-enabled (and, specifically, deep-learning-enhanced), self-conscious IoT-extended distributed CPSs*".

The IoT provides modularity and interoperability in the implementation of smart buildings by improving energy efficiency and indoor climate quality based on sensing, automation, and management [57]. The deployment of IoT-enabled sensors creates interconnected systems that constantly monitor environmental parameters in real time, offering important insights that are critical for decision-making and environmental management. IoT challenges include data security, privacy, and a lack of standardized communication protocols. Blockchain and advanced analytics are proposed to address these challenges. Practical application cases for IoT in PEDs include the following:

(i) *Smart Energy Management Systems*: Real-time monitoring and optimization of energy production, consumption and storage across the PED.
  - IoT-enabled meters and sensors track electricity, heating, and cooling usage.
  - AI-powered controllers adjust building systems (HVAC, lighting) based on occupancy and weather forecasts.
  - Integration into renewable sources (e.g., solar panels) and batteries to store excess energy and release it during peak demand.

(ii) *Building Automation and Optimization*: Dynamic control of building systems to improve efficiency and comfort.
  - IoT devices regulate temperature, ventilation, and lighting based on occupancy data.
  - Predictive maintenance alerts for HVAC systems.
  - Smart blinds and windows optimize natural light and thermal gains/losses.

(iii) *Energy Sharing and Peer-to-Peer Energy Trading*: Facilitation of energy exchange between buildings and prosumers within the PED.
  - IoT sensors measure energy production and consumption in real time.
  - Blockchain enables automated and transparent transactions.
  - Smart contracts manage energy pricing and distribution.

(iv) *Demand Response and Load Balancing:* Adjusting demand to match supply and reduce peak loads.
  - ■ Smart appliances and EV chargers respond to dynamic pricing signals or grid status.

- IoT platforms manage demand in real time, shifting non-essential loads to off-peak hours.

(v) *Integration with Mobility Systems*: Reduction of emissions and integrating energy use across transport and buildings.

- IoT-integrated EV charging stations optimize charging based on grid status and renewable availability.
- Connected bike-sharing or car-sharing systems reduce dependency on fossil-fuel transport.

(vi) *Environmental Monitoring and Adaptation*: Monitoring and responding to environmental conditions that affect energy performance.
Application:

- Sensors track air quality, humidity, temperature, and solar radiation.
- Data used to adapt building behavior or alert residents about pollution or heat stress.
- Integration into green infrastructure (e.g., smart irrigation for green roofs).

(vii) *Citizen Engagement and Behavioral Insights:* Promoting energy-saving behaviors through real-time feedback.

- IoT dashboards or mobile apps provide feedback on energy usage.
- Users receive tips, comparisons, or incentives based on their energy habits.
- Community-wide challenges to encourage reduced energy consumption.

(viii) *Urban Infrastructure Monitoring*: Monitoring and managing energy-related urban infrastructure for improved performance.

- Street lighting that adjusts based on pedestrian/cyclist presence and ambient light.
- Smart grids that detect and respond to outages or inefficiencies.
- Condition monitoring of district heating and cooling networks.

3.5. Edge Computing

Edge computing is utilized for growing computing and networking needs. It enables real-time processing and analysis, and reduces latency and bandwidth requirements. Hence, it offers innovative contemporary solutions for effectively monitoring remote areas. In contrast to traditional centralized servers, edge servers are located close to the network edge, to data sources, and to the end-users [58]. They can be found in smart homes, IoT-powered factories, and self-driving cars. Edge servers have powerful computing capabilities and can offer many advantages. Edge computing has the potential to harness the full computing capacity of both edge devices and edge servers. To obtain lower inactivity and preserve security and privacy, edge computing shifts data processing from centralized cloud servers to edge nodes closer to the source, facilitating management of the growing complexity and real-time requirements of IoT applications.

Moreover, edge computing supports PEDs through real-time data processing, energy management optimization, and integration of renewable energy resources at urban local level. By processing data near the points of energy production and consumption, edge computing enhances the efficiency, resilience, and sustainability of PEDs [59]. Dynamic integration of diverse renewable energy systems and multiple stakeholders is an explicit characteristic of PEDs that is supported by edge computing. This helps PEDs to become more resilient to energy disruptions and more adaptable to changing urban and climatic conditions [59].

For real-time systems, time-sensitive standards are fundamental in enabling low-latency and high-reliability communication [60]. Despite its potential, the energy efficiency of edge computing is still largely unexplored, due to the complicated structures and interactions between edge devices, edge servers, and data centers [58].

Because of the increased use of the IoT, challenges regarding management of huge volumes of data, which are usually of different types, have appeared. Additionally, complexity is amplified by the increasing number of cameras needed. The standard that exists today of using the IoT together with cloud computing has proven not to be sustainable [61]. Instead, by utilizing edge computing, IoT data is processed close to the location where the data is generated and Internet latency of data transmission can be efficiently reduced for time-constrained IoT applications [59]. Computation is performed locally, so the volume of data for transmission to remote data centers and cloud storage is minimized, the response time is reduced, and processing availability is improved. However, due to the complexity of edge-based IoT deployment, effective, efficient, and automatic management is needed [61]. Practical application cases for edge computing in PEDs include the following:

(i) *Real-Time Energy Monitoring and Optimization*: Edge devices monitor energy consumption and production (e.g., from heat pumps, solar panels) in real time through the collection of building-level data by a local edge server to fine-tune HVAC settings or battery storage use depending on demand and weather forecasts. This enables optimization of energy balance locally without the need for cloud computing.

(ii) *Demand Response Management*: Edge systems detect peak demand patterns (e.g., dishwashers, EV charging) and autonomously trigger load shifting or load shedding. As a result, grid stress is avoided and reliance on external control centers is reduced.

(iii) *Local Renewable Energy Integration:* Edge computing coordinates local energy generation (e.g., PV systems) and storage units (e.g., home batteries), and decides when to use solar power, store it, or feed it into the grid based on real-time conditions. This enables better self-consumption and local balancing of supply/demand.

(iv) *Microgrid Control and Islanding:* Edge computing enables a PED to switch into island mode and operate autonomously in case of grid failures for increased resilience and continuity of energy supply.

(v) *Smart Lighting and Street Infrastructure:* Edge nodes control public lighting based on occupancy, daylight, and weather; hence, unnecessary energy use and maintenance costs are reduced.

(vi) *EV Charging Optimization*: Local edge systems coordinate electric vehicle (EV) charging schedules. Hence, grid overload is avoided and charging is aligned with renewable energy availability.

(vii) *Building Energy Management Systems (BEMS) Integration*: Edge computing integrates diverse BEMSs across a PED for holistic energy management and coordinated scalable operation without reliance on a central cloud service.

(viii) *Occupancy and Behavioral Analytics*: Edge devices use occupancy sensors and machine learning to analyze usage patterns. For example, an edge AI model can adjust heating and lighting in shared spaces based on real-time presence detection. This improves comfort and energy efficiency without sending personal data to the cloud.

(ix) *Predictive Maintenance for Infrastructure*: Edge analytics monitor equipment (HVAC, solar inverters, etc.) for signs of failure. For example, local edge nodes detect anomalies in energy equipment and alert maintenance crews before breakdowns. This reduces downtime and extends asset life with minimal data transfer.

(x) *Security and Surveillance Systems*: Real-time edge-based video processing enhances safety with minimal bandwidth usage for improved security without the need to store sensitive video data in the cloud.

3.6. Blockchain

The aim of PEDs to generate renewable energy to a higher extent than they consume prompts a need for decentralized energy management and data transactions that are both secure and economic [62]. Blockchain, a distributed ledger technology, facilitates transparent and secure recording of data and transactions, which enables households, businesses, and PEDs to directly trade excess energy with each other. This decentralized approach validates and verifies transactions, and hence eliminates intermediaries (e.g., banks or governments), reduces waste, increases transparency and accountability in energy systems, reduces transaction costs, and promotes energy efficiency through more localized energy distribution [45]. Blockchain is associated with a decentralized privacy-aware data management framework for PEDs, allowing actors to read, modify, and store data with secure, effective, and scalable outcomes [63].

The use of blockchain is critical in enabling more transparent and more efficient energy systems [64]. As a result, blockchain-based architectures have been put forward to reduce the negative effects of climate change, such CO^2 emissions [65]. These aim to achieve the following:

- Promote effective integration of energy services delivered to the electricity grid by the PED;
- Support the development of a reliable certification system for energy self-sufficiency;
- Enable effective energy trading management among diverse PEDs.

Blockchain facilitates peer-to-peer energy trading and provides a secure and transparent platform for monitoring energy production, consumption, and storage. In addition, smart contracts based on blockchain are able to automate energy transactions and support energy conservation (the choice and practice of using less energy), which leads to both efficient and sustainable energy use [64].

Blockchain can enable the utilization of smart grid systems that use real-time data to optimize energy production, energy storage, and energy consumption. It can improve smart grids by applying decentralized energy management and data transactions, and by addressing cybersecurity and potential challenges related to scalability and market adoption. Smart grids are affected by blockchain development in different sectors, such as smart contracts and demand response, electric vehicles, IoT technology, energy trading, financial transactions, testbed, and environmentalism [62]. Below, some practical PED applications that use blockchain are presented:

(i) *Peer-to-Peer (P2P) Energy Trading*: Blockchain creates a secure, transparent ledger for energy transactions in local or consumer-centric marketplaces, enables smart contracts to automate buying/selling based on predefined rules, and decreases the need for intermediates [66].

(ii) *Decentralized Energy Management*: An important potential benefit of blockchain lies in its decentralized nature and robust security features [67]. Blockchain supports autonomous coordination of distributed energy resources through smart contracts (energy storage usage during peak hours is automatically shifted to balance the PED load), dynamic pricing models based on supply and demand, and local grid stability and load balancing. Complete decentralization of energy markets can be accomplished thanks to the capability of blockchain to enable cryptocurrency-based financial transactions within the energy industry. As a result, financial transactions will no longer need to be controlled from a single location [67].

(iii) *Energy Data Transparency and Traceability* of energy monitoring for consumption, production, and emissions data: Blockchain ensures robust records of energy flows, provides audit trails for carbon accounting and compliance, and supports real-time verification and certification of green energy trading [66].

(iv) *Secure IoT and Smart Meter Integration:* PED monitoring relies on IoT sensors and smart meters. Blockchain provides secure data channels and identity management, prevents tampering with device data, and ensures interoperability among devices and systems. Smart meters send real-time data to the blockchain for secure and auditable energy billing.

(v) *Carbon Credit and Emissions Trading:* Carbon credits are generated by producing clean energy and reducing emissions. They are used to weight emissions from various sources, are often issued by governments or international organizations, and can be traded on carbon markets. One carbon credit is equivalent to 1000 kg of carbon dioxide. The difference the carbon emissions allowed and those actually emitted is called carbon credit [68]. Blockchain supplies tokenized traceable unchallengeable carbon credits, facilitates transparent and automated trading of credits, and verifies emission reductions in real-time (via IoT sensors and blockchain logging).

(vi) *Tokenization of Energy Assets:* A considerable barrier in the energy sector is the financial strain caused by rising electricity costs. Blockchain allows fractional ownership of e.g., solar farms and battery storage by the use of tokens that correspond to shares in energy-producing assets, hence enabling micro-investments by citizens [69]. Residents invest a certain amount into, e.g., a solar farm and receive dividends or energy credits proportional to their stake

(vii) *Resilience and Disaster Recovery:* Ensuring energy services during grid outages or cyber-attacks. Blockchain supports off-grid P2P networks for energy resilience, maintains decentralized records for continuity in outages, and can automate fallback energy sharing strategies. In the event of a grid failure, the local PED automatically shifts to a backup mode, with blockchain coordinating energy distribution from batteries and microgrids.

4. Challenges and Potential Solutions in Utilizing Emerging Technologies in Positive Energy Districts

PED project challenges and barriers differ according to the development stage they are in [70]. The complex planning stage of existing urban refurbishment is, however, the most crucial. Practical PED experience is primarily based on recently built districts or planned future districts. However, considering that 85% of the buildings in the EU were constructed before year 2000 and that 75% of them display poor energy performance [71], the challenges will mainly be to refurbish existing buildings and regions to the standards of PEDs. The main challenges associated with the integration of PEDs in urban areas include the following [17]:

- Lack of accepted methods for assessing energy balances;
- Difficult to integrate renewable energy systems into redundant and old-fashioned urban infrastructures;
- Multi-stakeholder collaboration needed in order to secure local acceptance and safeguard reasonable development processes.

Other challenges, but also opportunities, can be found in data analysis, interoperability, business models, management, and data security. There are several barriers and challenges associated with the transition to renewable energy systems, including high initial expenses, and political and societal barriers [64].

As Krangås et al. [2] argue, the novelty, adaptability, and complicated nature of PEDs has led to numerous interpretations and definitions. This, in turn, has initiated challenges regarding implementation, evaluation, comparison, and replication of PEDs. They identified "*seven interacting challenges: governance, incentive, social, process, market, technology and context*" [2]. In this study, we mainly look at the challenges from a technological point of view, but as Krangås et al. [2] emphasize, a deeper cross-disciplinary understanding of the challenges is needed due to the complexity of developing PEDs. Hence, we also present other key barriers that may influence technical challenges. In the following subsections, challenges and potential solutions in using emerging technologies in PEDs are proposed.

4.1. Business Model Challenges in Positive Energy Districts

Effective business models for creating PEDs are crucial. A lack of coherent business models covering the needs of PEDs has been identified [72]. A complete financial strategy is often also missing. Regional and national grants together with private investment are mainly used for implementing PEDs. Innovative business and financial models constitute a significant challenge that needs to be addressed [70]. Factors that require further consideration in the PED business model are the following:

i *Economic Feasibility*: This is challenging because of high initial costs and the requirements of future financial robustness and sustainability. Although PEDs have a wide range of possible revenue streams, many cannot yet be fully materialized due to missing regulatory frameworks [73]. The cost of PEDs needs to further decrease, including technology introduction and integration.

ii *Balancing costs and benefits*: An effective business model should balance costs and benefits successfully to attract investment and safeguard profitability [2]. PED business models need to consider dynamic pricing, peak shaving (reducing energy consumption at times of high energy demand), new markets to be opened, and new products to be created.

iii *Complex stakeholder interactions*: Including multiple stakeholders with diverse interests and needs is challenging and requires adequate communication and collaboration strategies for aligning the various stakeholder goals and guaranteeing effective implementation. Cultural differences and social acceptance are likely to impact PED employment. Scaling up or replication of successful PEDs is challenging because different urban areas have different cultural, spatial, and social contexts. PEDs have a number of shared characteristics, despite the fact that they are very specific to their local context. Derkenbaeva et al. [74], for example, argue that "*real-life PEDs tend to go beyond the frames set by the definitions because the concept fails to consider the contextual factors that are inherent in them*". Another factor that is important for replication is difference in Key Performance Indicators (KPIs). As stakeholders may use various KPIs for PED assessment, agreement regarding value and impact may increase the challenges [75]. However, it is important to extract the maximum replication potential of a PED in the early design phase in order to allow tailor-made solutions for other local contexts [42].

iv *Local community and end-user engagement*: PED business models should contain strategies for local community engagement. Their concerns need to be taken into consideration in order to promote acceptance and participation. End-user and public awareness regarding the advantages of PEDs needs to be catered for [76].

v *Supportive policies and regulations*: These are imperative for the scalability and dispersion of PEDs. The regulatory landscape reveals a noteworthy challenge. Business models usually need to adapt to existing national and regional regulations despite the fact that local policies may not support innovative energy solutions [76]. Governance structures need to be flexible to allow for effective management of the complexity and interdependencies of PEDs. PED business models should be adaptable and include strategies for replication and scalability in different urban contexts, which are distinctive due to varying geographic, historical, and socio-economic conditions [5].

vi *Integrating contemporary technologies*: Integrating renewable energy systems (e.g., solar PV, wind turbines, and geothermal energy), energy storage solutions, smart grids, hydrogen fuel cells, and biofuels has been proven to be a complex task.

vii *Business models*: When creating business models, technological advancements and technology adoption should be taken into consideration to ensure the seamless integration of energy management optimization. The technological challenges include energy simulation, modeling, and performance assessment [2,77].

4.2. Technological Challenges in Positive Energy Districts

Automation indicates the reduction of human intervention in processes through the utilization of a wide range of technologies. In PEDs, buildings, cities, and districts create dynamic self-updating structures, automation, and interconnected infrastructures.

(i) *Automation of environmental sensing and monitoring:* Diverse challenges regarding the automation of environmental sensing and monitoring are listed, together with potential solutions for addressing these challenges [78]:

- *Amplified data exchange:* Due to amplified data exchange across urban areas, increased automation is increasingly being deployed to facilitate local governance and optimization of the services offered [45]. A lack of clear guidelines or standards for modeling these data flows, however, results in limited scalability and changing needs.
- *Accurate and precise data gathering:* Achieving accurate and precise data gathering by automated sensors and monitoring systems can be challenging—use of contemporary technologies for error detection and correction, sophisticated data collection techniques, and vigorous validation mechanisms will improve data correctness.
- *Changes in correctness of measures:* Due to, e.g., changes in environmental conditions (which may lead to changes in physical properties and samples), sensor drift (sensor output values changing over time), and calibration issues (comparison of measurement values delivered by a device under test with those of a calibration standard of known accuracy) are serious challenges that need to be identified at an early stage—implementation of strategies for data integration of environmental conditions, and performance of regular sensor calibrations and maintenance are potential solutions.
- *Incompatibility of data formats, resolution, and quality:* Unifying the data returned from remote sensors, satellite images, and ground-based stations is challenging—potential solutions include the application of data conversion to achieve the same format for all data.
- *High costs*: The upfront and continuous costs of automation technologies can be challenging—potential solutions include minimizing interruption, and frequent and regular maintenance, including sensor calibration, software and hardware updates, preventive maintenance, and deployment of automated monitoring systems.
- *Access to power, network connections, and infrastructure:* Data storage and data transmission are imperative for the smooth operation of PEDs. Potential solutions include automated monitoring to avoid disruptions.
- *Interdisciplinary collaboration:* A general approach, due to PEDs' complexity and interdisciplinary characteristics, to overcoming challenges concerning environmental monitoring and sensing automation is the collaboration of experts from

diverse fields, including computer systems, engineering, social and environmental sciences, and economics.

- *Security:* The privacy, safety, and security of CPSs in smart PEDs face considerable challenges because of their vulnerabilities to cyber-attacks. Robust security mechanisms to protect against threats like energy theft, grid instability, and unauthorized access are needed. Advanced cybersecurity measures, integrated frameworks, and innovative technologies (e.g., blockchain and quantum computing) can be used to ensure system resilience and protect the system against potential threats (e.g., attacks that create security deficits, affect national grid security, and cause life loss or large-scale economic damage from lack of integrity and confidentiality) [33].

(ii) *National security deficits and loss-of-life interdependencies between energy generation method (GM), control method (CM), and energy management system (EMS) topologies:* The local energy management system needs a decentralized management and monitoring system. However, interdependencies between energy GM, CM, and EMS topologies lack a distinct developed path and established target parameters to predict future directions for EMS research and to determine robust evaluation parameters for EMS proposals. Kudzin et al. [79] proposed blockchain-based architectures as a potential solution, which are well aligned with incoming decentralized GM and the limitations of CM requirements. Blockchain-based architectures offer adaptability, resilience, scalability, and security and can be considered an effective and efficient choice for a next-generation EMS.

(iii) *Communication, data, and physical interoperability:* In smart PEDs, digital systems are deployed that contain diverse service providers who collaborate to provide digital services to citizens. Due to lack of standardization of interfaces in isolated systems (vertical silos), they are seen as barriers regarding interoperability and the seamless transfer of data between systems. Bokolo [80] proposed the use of an Application Programming Interface (API) to enable seamless communication interoperability (interface, technology), data interoperability (syntactic, semantic), and physical interoperability (technical, network, device, platform). Another challenge is the interoperability of multiple neighborhood systems, which mainly stem from the incompatibility of the different systems used in the creation of a PED.

(iv) *Wireless sensor network (WSN) challenges* [78]:

- WSN security issues lead to a lack of communication between sensors and waste more energy. WSNs are disposed to failure due to their huge number of nodes and unique restrictions in both hardware and software [81]. The need for efficient solutions has increased, particularly with the rise of the IoT, which relies on the effectiveness of WSNs. Exploration of ML algorithms together with fuzzy logic has been proposed to increase reliability, particularly in mitigating node and link failures.
- Privacy issues may make WSNs risky [82]. Challenges such as privacy threats posed by smart objects, restriction regarding collecting and processing confidential data, and the regulation of using and distributing confidential data collected need to be considered. When creating new systems and services, users' requirements should be carefully examined and sensitive data should be responsibly handled.
- Sustainable operations in energy-constrained environments. To improve WSN performance, energy harvesting (EH) from environmental forces (Radio Frequency (RF) signal, sunlight, vibrations, wind, etc.) has been identified as a successful method for obtaining unlimited WSN energy [83]. EH-WSNs maxi-

mize the utilization of harvested energy by fine-tuning the operations of sensor nodes according to obtainable power. EH-WSNs enable wireless sensor nodes to prolong their lifetime and to minimize their dependence on constrained energy resources. Also, cognitive radio (CR) technologies are considered to improve spectrum efficiency and to enable dynamic spectrum access by identifying underutilized frequency bands. Security is a challenge in EH technologies. Physical layer security (PLS) has been proposed as a solution because it embeds security in the process of energy harvesting, and as a result, replaces classical encryption techniques [83].

- Time synchronization ensures that all nodes in a WSN share a common time reference, which is essential for accurately timestamping and correlating sensor data. If synchronization packets are delayed or lost, appropriate techniques (e.g., periodic resynchronization, local clock drift correction, etc.) and robust protocols should be used to help maintain timing accuracy [84].
- The efficiency and durability of WSN coverage as well as of route optimizations are pivotal, as WSNs can be rapidly deployed across wide or inaccessible areas. The requirement of gathering data from all network sensors creates limitations on the distance between them [85]. Sensor fusion techniques are employed to combine data from diverse sensors. The aim is to enhance the reliability of environmental monitoring and to provide a more comprehensive understanding of environmental conditions.

(v) IoT challenges [8]:

- The IoT enables the collection and analysis of real-time data from various energy sources [45]. However, IoT devices are vulnerable to cyber-attacks, which can lead to security threats, such as intellectual property theft, data breaches, and disruptions to critical infrastructure.
- Data confidentiality, security, and privacy: Security approaches aim to protect networks (data and devices) against malicious attacks and unauthorized alterations, as well as protecting the privacy of the users (protection of personal information from unauthorized access and misuse) [86]. The backbone of IoT network security consists of cryptography-based methods ensuring data privacy, integrity, and authentication. Resilience to various forms of attack is provided, whilst low scalability, usability, and efficiency are drawbacks.
- Functionality, safety, and fault tolerance: Industry 4.0 has introduced functional safety networks that provide enhanced production reliability, scalability, and flexibility. New contemporary applications have emerged that provide reliable coordination between ICT, sensors, and actuators [87].
- Quality of Service (QoS): Taking QoS characteristics into account, several quality approaches have been proposed at various layers of the IoT architecture [88]. QoS approaches must exist at every layer of the IoT architecture to guarantee a satisfactory level of QoS concerning safety critical applications of IoT.
- Standardization activities, protocols, and architecture: IoT platforms that integrate different element types provided by diverse vendors that use different protocols, different data formats, and different communication technologies is needed to monitor and control the device requirements [89].

Combining various technologies in PEDs is challenging. Hence, several tools are increasingly being used to manage energy more efficiently [14]. At the district level, tools such as “Geographic Information Systems” (GIS) and “Supervisory Control and Data Acquisition” (SCADA) are commonly used, while, at the building level, tools including “Building Management Systems” (BMS), “Building Energy Management Systems” (BEMS), "Computer Aided Facility Management" (CAFM), and "Integrated Workplace Management Systems" (IWMS) are often utilized [14]. For example, a new GIS platform has been developed to quantify the energy savings gained through application of refurbishment measures [4]. For each postal district, the GIS platform provides estimates for buildings with specific parameters and provides solutions for low-enthalpy geothermal energy and solar thermal energy in urban areas. Solar irradiation maps assess solar resources, whilst Google Maps estimates geothermal potential. Urban data has been derived from official cadastral (land registration) databases.

5. Relationships Between Emerging Technologies in Positive Energy Districts

To enhance understanding of the relationships between the emerging technologies considered important for PEDS, the interactions and relationships between the different technologies are described:

1. *Cyber-Physical System–Digital Twins:* DTs are digital models or virtual copies of a physical environment, including CPS infrastructure that adapts to real-time physical changes, and swiftly provide beneficial solutions for PED optimization [20]. DTs constitute a promising approach to realize CPSs [90] since they enable analysis, prediction, and optimization of the interconnected physical entities (e.g., energy optimization of BEMS) and support real-time decision-making. CPSs provide DTs with real-time data and control mechanisms which enable anomaly detection in maintenance and control stages and virtual testing [91]. Together, they are important tools for facilitating autonomous systems, smart cities, and PEDs. They can be used to forecast energy demand and end-user consumption patterns, as well as to schedule dispatchable energy generation from shifting renewable energy sources on demand [92].
2. *Cyber-Physical System–Artificial Intelligence:* AI supplies cognitive capabilities including reasoning, learning, and decision-making to CPSs. AI enhances CPSs' data-driven insights (e.g., real-time fault detection, optimization), intelligent control (e.g., adaptive controllers, predictive maintenance), and autonomous operation (e.g., self-driving cars, drones). The evolution of AI decision-making in cyber-physical systems is inevitable and autonomous due to increased integration of connected IoT devices in CPSs [93]. As CPSs generate enormous amounts of data from sensors and other physical components, AI processes and learns from this data and optimizes the behavior of CPSs, which as a result leads to improved data produced by the CPSs. This feedback loop continuously improves system performance. CPSs and AI together are essential for meeting PED positive energy targets due to energy management automation, adaptive control of building environments, and integration of distributed renewable resources [25]. The benefits of integrating AI with CPSs include reduced need for human intervention, improvements in fault tolerance and recovery, optimization of operations and resource use, and improved management.
3. *Cyber-Physical System–Internet of Things:* CPSs are complex multi-layered feedback systems that interact with the physical environment through the IoT, which offers pervasive sensing and communication infrastructure to CPSs [32]. CPSs may be focused on, e.g., building real-time applications or providing customized services in the context of the IoT [93]; hence, the IoT is advanced via CPSs due to the introduction of advanced control, automation, real-time processing, decision-making capabilities, and integration within physical processes enabling dynamic optimization of energy flows and system resilience. A CPS usually includes IoT elements, but not all IoT systems classify as CPSs. When CPS is the goal, the IoT is part of the infrastructure necessary to achieve it.

4. *Cyber-Physical System–Edge Computing:* A variety of large-scale CPS applications have been widely deployed, such as smart grids, intelligent transportation, and personalized healthcare, with strict real-time requirements due to the fact that delayed outputs may give rise to unacceptable timing faults [94]. CPSs generate data that edge nodes receive and process, and, in turn, edge computing enables CPSs to meet timing constraints, reducing latency challenges. Moreover, edge computing reduces the load on central systems, making CPSs more scalable, and improves privacy by keeping sensitive data local. In addition, edge and CPS integration increases fault tolerance and can save energy in CPS systems by applying local processing. For example, in smart grids, local edge nodes manage energy distribution based on real-time data from CPS components.
5. *Cyber-Physical System–Blockchain:* Blockchain complements CPSs by supplying transparency, trust, and secure coordination between distributed digital and physical components. Blockchain enhances CPS security by providing an immutable history of CPS actions and events, improving data protection, increasing trust between system participants, and automating processes using smart contracts, as well as enabling forensic analysis in the event of an attack or system failure [95]. Blockchain, together with smart contracts, enables distributed control logic and decentralization of energy markets by utilizing cryptocurrency-based financial transactions. The synergy between CPS and blockchain shows promise for progressing the development and operation of sustainable, secure, and efficient PEDs [96].
6. *Digital Twins–Artificial Intelligence:* DTs and AI are two different but complementary technologies. DTs are digital copies of a physical asset that collect information from IoT devices, and apply advanced analytics, ML, and AI real-time processed data about physical assets' lifecycle process [25]. When integrated, they can significantly improve system performance, predictive capabilities, and decision-making. Two AI techniques, ML and NLP, are instrumental in modeling, extracting, and mapping the complex elements of PEDs, facilitating tasks like demand forecasting, system control, and stakeholder mapping [42]. AI instills intelligence in DTs by analyzing large volumes of sensor data in order to detect patterns, anomalies, and trends, while DTs provide the data and real-world context that AI needs to perform. ML models predict future states or failures, making DTs predictive instead of descriptive. Moreover, AI optimizes system parameters or processes in real-time by running simulations through the DT. AI integrated with DT can provide urban traffic management, and energy optimization with grid management and forecasting in renewable energy systems.
7. *Digital Twins–Internet of Things:* The relationship between DTs and the IoT in the context of PEDs is both complementary and synergistic. The two technologies interrelate and reinforce each other in the development and management of PEDs. DTs can be divided into three parts: the physical product, the virtual product, and the communication infrastructure/data collection systems. A critical aspect of the DT is the connection between the physical twin and the digital twin, which consists of IoT sensors and actuators [91]. The IoT continuously feeds DTs with accurate data, ensuring a trustworthy digital model, and, in turn, DTs simulate future scenarios using IoT data to visualize IoT data, guide and direct energy management, and facilitate intelligent control of PED operations. For example, at a microgrid network level, a vast number of assets, sensors, meters, controllers, and actuators are connected to the Internet through diverse IoT communication networks [97]. The integration of DTs and IoT creates a feedback loop that continuously improves PED energy performance.

8. *Digital Twins–Edge Computing:* DTs and edge computing form a synergistic pair in PEDs. Integrating DTs with edge computing in PEDs enables real-time, efficient, and secure resource management, data synchronization, and service optimization for smart grids and urban energy systems [98]. DTs provide the intelligence and simulation capability, while edge computing enables local, fast, and secure execution of the DT insights, and, together, they enable PEDs to be more responsive, efficient, and sustainable. In general, DTs involve sensitive urban data, such as residents' energy usage, but when processing data at the edge, unnecessary personal data transmissions are minimized and compliance with privacy regulations and data sovereignty is enabled.
9. *Digital Twins–Blockchain:* The integration of DTs and blockchain holds significant promise in the context of PEDs. Blockchain validates and secures the data stream feeding the DTs, ensuring that simulations and decisions are based on tamper-proof, verified inputs. DT forecasts inform the blockchain's smart contracts when and how much energy can be traded, creating an autonomous self-regulating PED. Blockchain reinforces trust in the data and models used by DTs, enhancing multi-stakeholder collaboration. The integration of DTs with blockchain enables the creation of decentralized energy trading platforms, P2P transactions, and the use of smart contracts, promoting trust and automation in energy exchanges [99]. Blockchain-enabled DT grids offer strong cybersecurity, protection of energy systems from cyber-attacks, and safeguarding of data integrity, as well as optimization of energy production, distribution, and consumption, while preserving privacy and detecting malicious behavior [100]. This synergy is significant for next generation of smart grids and PEDs, enabling resilient, sustainable, and user-centric energy systems that align with global sustainability goals [101].
10. *Artificial Intelligence–Internet of Things:* The relationship between AI and the IoT is central to the development and operation of PEDs. The increased utilization of renewable energy sources requires infrastructure re-structuring, enabling grid development and AI usage for distributed and intermittent generation. The integration of AI, IoT, and blockchain technologies into energy and power systems improves efficiency, sustainability, and reliability [102]. The integration of AI and the IoT is significant for smart, sustainable urban energy systems. IoT applications in building energy management, enhanced by AI, are able to transform how energy is consumed, monitored, and optimized, particularly in distributed energy systems [103]. By using IoT sensors and smart meters, real-time data regarding PED energy usage patterns, occupancy, temperature, and lighting conditions can be collected. This data is analyzed by AI algorithms to identify inefficiencies, predict energy demand, and suggest or automate adjustments to optimize energy use. In PEDs, the IoT provides the data infrastructure, while AI provides the intelligence needed to orchestrate complex systems and ensure the PED produces more energy than it consumes.
11. *Artificial Intelligence–Edge Computing:* The relationship between AI and edge computing in the context of PEDs is very synergistic. An edge-AI-based forecasting approach is proposed to improve satisfaction with prediction accuracy and smart microgrid efficiency by analyzing and processing consumer power data and distributed renewable energy generation [104]. The integration of AI and edge computing facilitates real-time, intelligent, and decentralized management of energy systems in urban environments, aiding PEDs to reach their goal of annually producing more energy than they consume. Moreover, the integration of AI and edge provides many benefits for the Internet of Energy, such as reduced latency, real-time analytics, improved

security, enhanced scalability, and better cost-efficiency, but faces challenges such as security and standardization [105].

12. *Artificial Intelligence–Blockchain:* The connection between AI and blockchain in the context of PEDs consists of influential synergies for advancing sustainable urban development. AI enhances energy management by predicting demand, optimizing consumption, and enabling real-time control, while blockchain provides secure, transparent, and decentralized platforms for energy trading and certification of energy self-sufficiency within and between DEPs [106]. The integration of AI and blockchain enables prosumers to participate in energy markets and contribute to the optimization of power system operations; hence, they support net zero emission targets. This integration also enables autonomous, self-regulating, intelligent, efficient, trusted, and transparent energy systems, where PEDs not only sustain themselves but contribute positively to the broader grid and the environment.
13. *Internet of Things–Edge Computing:* In the context of PEDs, both the IoT and edge computing play critical and complementary roles. Their relationship is central to achieving the real-time monitoring, optimization, and efficiency required in PEDs. Edge computing can reduce latency and bandwidth consumption by processing data on IoT devices or near them [107]. The IoT captures the necessary real-time data, while edge computing ensures that this data is acted upon swiftly and locally, reducing dependency on centralized systems. Together, they help PEDs achieve efficiency, sustainability, and autonomy.
14. *Internet of Things–Blockchain:* The relationship between IoT and blockchain within PEDs is emerging as a critical synergy for achieving efficient, secure, and sustainable energy systems. This synergy enhances trust among stakeholders, supports automated settlements, and facilitates the integration of renewable energy sources. Blockchain enhances energy efficiency in IoT-enabled energy systems by ensuring data immutability and transparency [108]. Moreover, blockchain can address the IoT's security and privacy challenges, ensuring safe data transmission and robust resource allocation in complex, heterogeneous energy systems. A proposed approach based on IoT components, blockchain, and smart contracts stores data and adds a reward and penalty strategy to the payment strategy, a basic feature of blockchain [109]. In PEDs, the combination of the IoT and blockchain creates a robust, transparent, and autonomous energy ecosystem. The IoT ensures real-time control and data collection, while blockchain guarantees security, transparency, and decentralization, enabling smart, sustainable urban environments.
15. *Edge Computing–Blockchain:* Edge computing and blockchain are increasingly being integrated to support the development of PEDs. Edge computing enables real-time data processing and decision-making close to energy sources and consumers, reducing latency and improving system responsiveness, while blockchain provides a secure, transparent, and decentralized platform for energy transactions and data sharing. This combination enhances trust, privacy, and security in energy trading, with efficient peer-to-peer transactions and protection against cyber threats in smart grids and microgrids [110]. Edge computing with blockchain can optimize energy trading, reduce operational costs, and improve the reliability and efficiency of decentralized energy systems [111]. Overall, the synergy between these two technologies is pivotal for enabling secure, efficient, and scalable energy management in PEDs. The combination fosters resilience, transparency, autonomy, and efficiency, which are all critical to the successful creation and operation of PEDs.

Table 1 illustrates the core benefits of each emerging technology in the context of successful creation and operation of PEDs. A potential PED case study utilizing these emerging technologies could be designed as follows: IoT sensors monitor solar panel output and building energy use. Edge computing locally analyzes whether to store or use energy. AI models predict energy needs based on weather and behavior patterns. A DT simulates district energy flows to optimize operations. Blockchain enables secure, transparent trading of excess energy between buildings.

Table 1. Integrated technology benefits in a PED.

Technology	Contribution to PEDs
CPS	Energy infrastructure real-time control
IoT	Real-time data collection from buildings, devices, and environment
Edge Computing	Low-latency processing and distributed decision-making
AI	Intelligent optimization and forecasting
Digital Twin	Simulation and monitoring of entire energy ecosystems
Blockchain	Trust, security, and decentralization of energy transactions

6. Discussion

The EU 2050 goal of achieving climate neutrality and a net-zero GHG emissions economy is promoting the concept of a positive energy balance. Attempts are being made to decrease energy consumption by introducing smartness. Renewable energy will be generated locally and will surpass consumption, which could lead to a decrease in overall energy demand and a reduction in GHG emissions.

New technologies are increasingly being used to improve sustainable development and to achieve the sustainable development goals [112]. PEDs strive to generate more renewable energy than demand requires while ensuring adequate comfort levels. A considerable aim of a PED is to improve the affordability and uptake of smart energy management systems, and to enhance local energy systems' flexibility by diminishing peak power demand and maximizing self-consumption through the utilization of energy management, smart grids, and battery storage. This flexibility is significant for the creation of new connections and the development of renewable energy production, particularly in locations with infrastructure constraints in the existing grid. Therefore, PEDs strive to increase energy system resilience and reliability. Another significant PED aim is to involve local stakeholders, including citizens, in governance. Through energy community engagement opportunities, they can influence and interact with the energy systems, enhancing PEDs' societal goals.

Insights from existing PED approaches have shown that the planning and timing of the development of a PED and its components are crucial for its success [113]. In this sense, artificial intelligence and machine learning techniques can be used to further optimize the planning, monitoring, implementation, and operation of various processes, including those involved in PEDs [114]. Identifying regulatory and legislative barriers when designing the governance of energy communities is also an important factor for the success of PEDs. According to Boshi et al. [9], the key PED success factor, as identified by 29 PED representatives, was "*Stakeholder involvement*", followed by "*Integrated technology*".

This study aimed to reveal emerging technologies that enable the adoption of PEDs by identifying the main challenges and potential solutions for effective implementation of PEDs. The results of the critical literature review revealed that CPSs are not standalone systems but are deeply interconnected with several innovative technologies including DTs, AI, IoT, edge computing, and blockchain technologies.

CPSs can increase the resilience, efficiency, and management of PEDs by integrating digital monitoring, control, and social engagement. They enable holistic coordination between physical infrastructure, digital systems, and social stakeholders. They enhance building energy management and energy efficiency by integrating and managing renewable energy flows, and by optimizing energy consumption based on occupancy and human behavior. As a result, they increase the resilience, security, and reliability of energy systems. However, they also introduce new cyber security challenges.

DTs improve PEDs by optimizing energy management, supporting stakeholder collaboration, improving sustainability, enabling real-time monitoring, and facilitating decision-making and stakeholder participation. They continuously track energy consumption, energy production, and energy storage by collecting and managing data from sensors, IoT devices, and BIMs. Hence, they facilitate proactive management and optimization of energy systems within districts, and they are essential for optimizing energy flows, supporting participatory planning, and ensuring the sustainability of PEDs.

AI can improve the planning, optimization, characterization, and communication of PEDs, hence supporting their development and the broader clean energy transition. Used in energy efficiency optimization, AI adapts and learns from data, which enables improvement of strategies related to energy saving. AI can positively contribute toward the achievement of sustainable development goals, promotes utilization of renewable energy sources, and enables optimization of energy consumption based on occupant patterns, weather conditions, and energy prices [80]. Decreased GHG emissions and reduced energy costs are benefits of energy efficiency optimization.

The IoT gives rise to considerable PED energy savings and CO^2 decreases due to smart data collection, smart information processing, and smart grids. As a result, PED sustainability and efficiency is enhanced. The IoT is important for successful implementation of PEDs, because of real-time monitoring, progressive energy management, and efficient incorporation of renewables. The IoT promotes sustainability, resilience, and a surplus energy balance in PEDs by linking and optimizing various energy resources.

Edge computing can further enrich PEDs by improving energy efficiency, optimizing renewable energy use, reducing reliance on non-renewable energy, and supporting resilient, sustainable urban energy systems through optimized task allocation and energy management. Edge computing plays a crucial role in enabling PEDs through real-time data processing and energy management optimization. Finally, edge computing enhances the efficiency, resilience, and sustainability of PEDs by bringing computation closer to the energy production and consumption points.

Blockchain enhances PEDs by enabling secure and transparent energy trading, improving data management and integration, supporting peer-to-peer transactions, and fostering stakeholder engagement and renewable energy integration. Using blockchain is essential in enabling a decentralized, transparent, and efficient energy system.

The results of this study highlight that the use of emerging technologies, including CPSs, DTs, AI, IoT, edge computing, and blockchain, is imperative for successful PED development and operation. However, the study also revealed key challenges that need to be addressed for PEDs to be further developed and adopted. All six emerging technologies were analyzed and their interrelationships were emphasized. How all six review concepts could interact within a PED is described in the following simplified case: CPSs offer real-time control and optimization of energy generation, storage, and usage enabled by IoT sensors, which monitor environmental factors and energy use, allowing data exchange and remote control. CPSs offer seamless integration of renewable energy sources and smart grid components, as well as improved fault detection and rapid response to anomalies. AI enables autonomous decision-making and autonomous smart energy system management that reduces waste and costs. It facilitates energy demand and supply prediction based on behavior patterns and weather conditions for optimal resource allocation. AI also enhances user engagement through personalized energy-saving suggestions. DTs are virtual representations of a physical asset/system (i.e., PED) that mirror its performance in real time by simulating energy flows for optimization of operations and assets. They facilitate predictive maintenance of PED infrastructure. Edge computing locally analyzes whether to store or use energy. It performs low-latency processing for fast, local decision-making and enhances system reliability and resilience. Blockchain ensures secure, transparent, and decentralized energy transactions; hence, it facilitates peer-to-peer energy trading within PEDs. To answer the RQ set, based on the aforementioned example and the overall outcomes of the study, it becomes clear that utilizing these technologies within PEDs can greatly influence PEDs, and that this is achieved in different ways and to various degrees.

7. Conclusions

A comprehensive critical literature review methodology was used in this study, which involved an extensive literature review with content analysis, enabling an in-depth exploration of the research topic and addressing the study objectives. The objective of the study was to comprehensively investigate the challenges, opportunities, and role of autonomous CPSs and technological innovations enabling smart PEDs. The shift to sustainable energy is critical for both economic and environmental reasons. It helps reduce the effects of climate change, lowers reliance on fossil fuels, and fosters economic development. The findings from this study can inform policy makers and future researchers regarding utilization of autonomous CPSs and technological innovations to integrate renewable energy sources and obtain sustainable energy solutions and intelligent, energy-flexible, and energy-efficient PEDs.

Several challenges were identified in transitioning to sustainable energy within PEDs, including security risks, technical complexity, and scalability, all of which must be addressed to effectively support a sustainable energy shift. In addition to understanding how autonomous CPSs and technological innovations can drive smart PEDs, it is essential to recognize that their development requires not only technological advancements but also policy changes that encourage investment in renewable energy technologies and promote sustainable energy use, production, distribution, and storage.

There are many opportunities to explore, including job creation, economic benefits, a cleaner and more sustainable environment, and greater citizen involvement, which need to be further examined.

This study contributes to the understanding of the concept of PED, as well as its success factors, barriers, and interdependencies. The focus of this study was to add a comprehensive, broadened view of emerging technologies to the existing PED literature. The presentation of practical PED applications for all the emerging technologies, considered important to the successful utilization of PEDs, and the relationships between them, aimed to improve the understanding of the complex interrelations between them.

Future research directions include a focus on the development of CPS architectures that are adaptable and scalable, and effectively deal with the decentralized and dynamic nature of energy production, consumption, and storage. Future research directions could also include an application of quantum computing, which can provide optimal or near-optimal solutions for energy management with computation times that scale positively as the problem size grows [115]. Theoretical and empirical analyses also indicate that quantum optimization algorithms can be two to four times more energy-efficient than classical ones, and quantum annealers may offer even greater efficiency gains [116]. As renewable energy integration increases system complexity, quantum computing is a promising emerging tool for energy optimization, in particular regarding complex systems including power grids, microgrids, and energy communities. Quantum algorithms, such as the Quantum Approximate Optimization Algorithm (QAOA) and quantum-inspired metaheuristics, have been proven to efficiently solve challenges of resource allocation, scheduling, and unit commitment that for classical computers are computationally intensive [117]. Quantum machine learning and reinforcement learning methods have also been applied to mobile edge computing and IoT scenarios, yielding important improvements in energy efficiency and learning speed compared to classical benchmarks [118]. However, current quantum hardware shows limitations in scale and noise, restricting practical applications to small or simulated systems [119]. Further research is needed to realize the full potential of quantum computing in real-world energy infrastructure. Finally, as this study focused on an overview of the field, there is a clear need for systematic literature review studies that have a more specific focus and explain the key enabling technologies of PEDs in more detail.

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