A Blockchain-based Platform for Positive Energy Districts

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***Abstract*—The reduction of climate change effects (mitigation) is now mainly driven by the limitation of CO_2 emissions which is currently becoming increasingly necessary and urgent to achieve. In this context, within the past Horizon 2020 program, the Urban Europe Joint Programming Initiative aimed to promote the development and deployment of at least 100 Positive Energy Districts by 2025. The latter are flexible, energy-efficient urban areas or groups of buildings that produce zero net CO_2 emissions and actively manage annual renewable energy surplus production at the local or regional level. As they are connected to the electric power system, Positive Energy Districts have the ability to offer flexibility services to the grid, such as frequency or voltage regulation, being part of a larger scheme as the Italian energy communities recently regulated by the Milleproroghe Decree. In this paper, a blockchain-based architecture is proposed with the aim of providing a system for the trusted certification of energy self-sustainability and the management of energy trading among different districts or the supply of energy services delivered from the district to the electricity grid, promoting their effective integration with the power system.**

***Index Terms*—Blockchain, Positive Energy Districts, emissions reduction, production certification.**

I. INTRODUCTION

Global warming is an issue that puts the various countries of the world in a position of extreme attention towards a response aimed at facing the climate emergency. Data from multiple studies show that climate change in the last decade has resulted in an increase in extreme weather events such as heavy rains and heat waves. However, an immediate and large-scale reduction of Greenhouse Gas (GHG) emissions and the resulting decrease of CO_2 concentration in the atmosphere can limit climate change. In this context, the European Union and its member states have signed the Paris Agreement through which the states themselves are committed to making the European Union the first zero climate impact economy and society by 2050. It is in this scenario that solutions are being tested in all sectors with the main objective of achieving carbon neutral status. In the electricity sector, this translates into an energy production increase from renewable sources which, through efficient management of the energy produced, leads to a decrease in the demand for supply from the traditional electricity grid and therefore a reduction in energy generation from fossil fuels. To achieve this, attention has also been paid to buildings or building aggregates (districts). Buildings in the European Union account for 40% of energy consumption produced and 36% of GHG emissions [1]. The energy demand is covered not only by fossil fuels but also by renewable energy sources. The ”Clean Energy Package” presented by the European Commission has promoted since 2016 through specific directives the use of renewable energy and energy efficiency with the goal of 32% production from renewable sources and the increase of energy efficiency to 32.5% by 2030 compared to 1990 levels. In addition, in order to reduce the environmental impact of buildings, EU Directive 2018/844 (EPBD- Energy Performance of Building Directive) on energy efficiency and energy performance of buildings was introduced in 2018.

The concept that has started to gain popularity is the Nearly/Net Zero Energy Building (NZEB) [2]; a concept that has recently evolved into Positive Energy Building (PEB) [3]. In general, the concept of PEB refers to an energy-efficient building that generates more energy from renewable sources than the building itself consumes and that, by providing comfort levels, is ecologically and economically sustainable. This condition can be achieved by reducing consumption and increasing energy efficiency rather than focusing exclusively on generation from RES. PEBs should be able to host and integrate future and innovative technologies, such as electric vehicles, smart appliances, and ICT systems, in order to better manage energy surplus through grid sharing and self-consumption. The PEB concept is an evolution of the NZEB by focusing on energy surplus management, rather than simply net balance. If in a given area there is a relevant concentration of PEBs, it is possible to speak of Positive Energy District (PED) [4]. PEDs are defined as energy-efficient and flexible urban areas or groups of connected buildings that produce zero net GHG emissions and actively manage annual renewable energy production at the local or regional level. From an energy perspective, the transition from PEB to PED offers the opportunity to achieve high levels of energy efficiency and RES generation through shared resources and energy needs. Energy efficiency actions at the single building level allow for a reduction in overall district demand, and coupling with technologies such as renewable energy systems, local energy grids, and storage can offer cost-effective solutions

The research is supported by the Research Project BLORIN – Blockchain for decentralized management of renewables, PO FESR Sicilia 2014/2020 – Action 1.1.5 - identification code: SI_1_23074 CUP:G79J18000680007.

as well. Compared to individual buildings, PEDs allow for greater precision in measuring energy performance and better management of demand and generation flexibility. In fact, districts are able to use multiple energy resources and have a larger available area than a single building site.
In Europe, in the framework of the European Strategic Energy Technology plan (SET plan Action 3.2) the development of PEDs is promoted by JPI Urban Europe Programme on Positive Energy Districts for Sustainable Urban Development plan (PED Programme), joined by 20 EU member states and started in 2018 with the goal of creating 100 positive urban energy districts in Europe by 2025 [5]. Although many European cities are moving towards low-carbon energy solutions, to date there is no common definition, guidelines or regulatory framework to ensure the feasibility of PED projects. Moreover, the implementation of PEDs is also limited due to the lack of management and certification systems that can help users to manage the district and interface it with the power grid. From the electrical point of view, if managed optimally, PEDs can have a positive impact on the power system and can be considered as new actors in the energy market, able to self-supply and at the same time provide ancillary services with benefits for both the grid and the district users. The successful operation of PEDs requires a high level of interoperability between the systems and equipment of the various stakeholders, including the exchange of data in a secure way. New information technologies such as blockchain can contribute to the deployment and development of PEDs by providing platforms for secure data management and certification ofself-consumption or management of energy service exchanges among PEDs and among PEDs and the grid. A smart management system would enable control and optimization of energy flows by connecting and balancing local RES supply and demand, including Electric Vehicles charging stations for load transfer and energy storage. In the literature, there are not many works integrating PEDs and blockchain, mostly they present use cases [6], [7] and benefits that this technology enables when used in the energy sector are analyzed [8], [9]. Only the work in [10] shows a blockchain-based system for decentralized data management that allows users of PEDs to store, read, and modify data, while the work in [11] proposes a possible blockchain-based solution to resolve several issues in data management, security, and community integration for PEBs.

About the development of blockchain platforms for the management of PEDs, analogies can be made with the work on the most current renewable Energy Communities (EC) introduced by the European Directive 2018/2001/EU (RED-II). For example, the work in [12] investigates various aspects regarding the interaction of renewable energy communities with the electricity system, highlighting which issues still need to be addressed for a full implementation and for their integration into the electricity system and how the blockchain can help overcome such issues. The paper in [13] analyzes how the use of blockchain can enable the interpretation of the RED-II directive for the development of Renewable Energy Communities, while in [14] a blockchain application for tracking the energy flows of public buildings and energy communities through the use of blockchain-enabled smart meters is described. In this paper, a blockchain platform for PEDs is presented with the aim of providing a system for continuous monitoring, certification of energy self-sufficiency and the exchange of energy services with the power grid in a transparent way and without the need for trusted third parties, while promoting their development and integration with the power system. Being a PED is not a matter of one-time certification that assesses that a district has a positive energy balance, but it is rather a dynamic concept. This is why we need distributed and continuous monitoring mechanisms to define PEDs. The work is organized as follow: in Section II the PEDs are defined and the main projects in Europe are presented, in Section III an overview of the main application of the blockchain technology for the energy sector is given, while Section IV describes a new blockchain-based architecture for PEDs management and certification.

II. Positive Energy Districts

The concept of Positive Energy District (PED) does not yet have a clear and unique definition, however in the last decade it has gained increasingly interest. PEDs are included among the useful means to reduce CO2 emissions in Europe and worldwide [15]; many scientific projects and regulatory institutions are focusing on the concept of PED, with the aim of promoting the spread of renewable energy sources, decrease the overall GHG emissions, increase the energy flexibility of buildings and promote the comfort for users [16], [17].

In general, a PED can be defined as an energy efficient and flexible urban area that produces zero net GHG emissions and is capable of managing energy flows and an annual surplus of energy production [18]. A PED consists of several energy interconnected buildings, connected to the power grid (on-grid) and able to exchange bidirectional energy flows, as shown in Fig. 1.

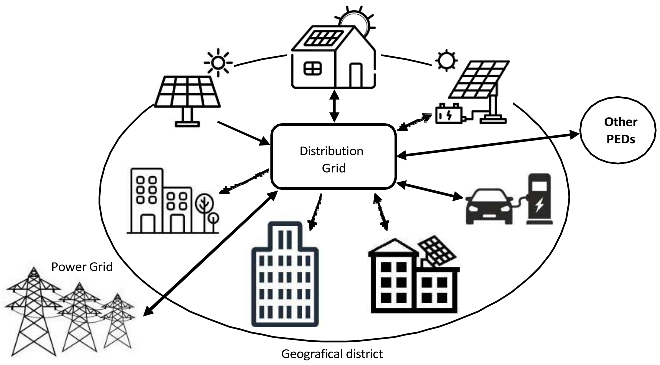

Fig. 1. On-grid PED architecture.

PED actions cannot be limited to energy surplus management, but must operate to maximize its impact on the electrical grid by implementing load management and self-consumption criteria, also including storage systems, Demand Response and Vehicle to Grid. So, a smart management platform for the buildings and services included in the PED is essential, to facilitate demand coverage with local generation, help the grid and turn a city into carbon-neutral. In Europe, the study of PEDs is largely driven by the European Commission, which in European SET Plan Action 3.2, included in the Horizon 2020 funding plan, makes it clear that PEDs are crucial to achieving zero emissions [19]. Specifically, JPI Urban Europe is a Horizon 2020-funded international research program focused on PEDs and urban transition, which includes several projects across Europe, some of which have already been completed [20]. There are several European projects that aim to study PEDs, including SPARCS, POCITYF, +Cityx-Change, ATELIER, and Making City. The SPARCS [21] project involves seven European cities and aims to monitor and develop innovative systems to achieve carbon neutrality. In two of the seven cities, Espoo (Finland) and Leipzig (Germany), PEDs are being implemented focusing on heating systems and mobility, which are the main sources of emissions in the two areas. The project includes the implementation of an integrated ICT network in the urban area and the development of a human-centric model, which increases the comfort of users. The POCITYF [22] project plans to implement PEBs and PEDs in two European cities, Alkmaar (The Netherlands) and Evora (Portugal). In this case, the goal is also to reduce users' energy bills. ATELIER [23] +CityxChange [24], and Making City [25] are projects with similar targets and characteristics, and involve more than 25 cities in Europe. All the above projects are linked by the same common thread: in order to reduce emissions and manage a surplus of energy from renewable sources, they need ICT platforms able to support complex interactions between the various buildings, services and facilities, and allow users to interact with the system. For the proper operation of the system, there is often a need for an Energy Management System (EMS) that allows monitoring, control and networking of all elements of the district. Therefore, the need for a platform to manage energy surplus and flexibility to maximize efficiency and self-consumption emerges. In addition to the optimal management of energy flows, an ICT platform would allow to evaluate the performance of PEDs [26]. The PED must be able to help the network in which it is integrated, through its flexibility and its energy flows; for this reason it is important to properly evaluate the level of building-network interaction. For example, in [27] two indices are proposed, one that identifies the interaction with the grid from the PED's point of view and another that represents the PED's ability to respond to external signals, such as price or production variations. The indices are useful to suitably vary load, generation or storage utilization. While, the work in [26] proposes a set of indicators useful for defining and measuring the annual energy balance of a PED; the most important is defined as the On-site Energy Ratio (OER) and measures the ratio of the PED's energy demand to the energy produced from on-site renewable sources. In view of monitoring, optimal management and certification of PEDs' performance, blockchain technology offers many advantages, enabling the development of management systems, transparent certification or evaluation of the above parameters without the need for trusted third parties.

III. The Blockchain Technology for Energy Services

The blockchain is an innovative technology based on Distributed Ledger Technology (DLT) [28] where, unlike a classic centralized server system, transactions are stored on all nodes of the network and there is no need for a trusted third party. In fact, the novelty introduced by the blockchain is to transfer trust from the single party to the whole network of nodes. The blockchain solves two important problems of a centralized system: the trust in the ledger manager and the weakness related to a possible attack on the central server, i.e. the single point of failure. In a blockchain, the ledger consists of blocks; in a nutshell, the blockchain is a chain of blocks, each of which contains a set of transactions. Each block is identified by a header, which is a unique string derived from a deterministic cryptographic function called a hash function. The block header also depends on the information of the previous block, so the modification of a block involves the modification of the whole chain, hence the immutability property of the blockchain. In order for a new block to be added to the chain, its authenticity needs to be approved by most of the nodes in the network. This mechanism is called consensus and allows the transfer of trust from a single user to the entire network [28], [29]. Finally, the blockchain allows for the implementation of Smart Contracts (SCs), which are contracts between the users in the form of code executed and shared on the blockchain nodes, allowing them to perform actions when certain established conditions are met [29]. The decentralized structure and consensus mechanism ensure that the blockchain has the characteristics of transparency, trust, and immutability; the blockchain is also reliable, (since there is no single point of failure) scalable (the system can be expanded easily), integrated (it allows connecting different users and machines, as long as there is a common communication channel) [30].

In recent years, blockchain has been used in many sectors, from finance to healthcare to agriculture, and in particular it is gaining importance in the energy sector [31], where it finds three main applications:

- electricity trading;
- RES certification;
- tracking and management of demand response service.

The traditional power system is evolving from a centralized structure, with a direct power flow from big power plants to the end-user, to a distributed one, with bidirectional power flows on all voltage levels due to distributed generation from small RES plants. This new energy scenario requires innovative business approaches, such as peer-to-peer (P2P) or business-to-business (B2B) [32], [33]. In P2P or B2B systems, energy is directly sold and purchased by end users, who can be prosumers or just consumers. There are several examples of companies offering blockchain platforms for P2P energy trading; some of these companies are: Green Power Exchange (US and China), Greeneum (US), Pylon Network (Spain), WePower (Spain), Conjoule (Germany), Electron (UK) [33]. A blockchain platform allows end users to participate in the electricity market, contribute to regulatory services, and generate aggregated virtual units for the provision of energy services without the need for an aggregator.

Another area where blockchain is gaining popularity is in electric mobility and related services, such as Vehicle to Grid [34]. The Mobility Open Blockchain Initiative (MOBI) [35], a consortium that aims to define a standard for blockchain technology for electric cars, V2G, and P2P applications was created in 2020. Honda, BMW, and General Motors are among the sponsors of the consortium.

Blockchain enables secure and transparent aggregation of both domestic and industrial users for the provision of energy services such as DR to overcome problems on the grid caused by RES or aggregation of local resources for participation in balancing markets. For this goal, some studies aim to emphasize that this new technology can help grid operators address load management issues. In [36], a blockchain platform is presented to aggregate loads, compute user Baseline and perform DR events. The DR event logic and baseline calculation is performed through the implementation of a SC, which also verifies the contribution of each user and calculates the remuneration. Another example is the BloRin project [37], which has among its purposes to use a blockchain platform to aggregate flexible loads and manage DR events in two Italian islands (Lampedusa and Favignana). Finally, blockchain is a useful tool for tracking the origin of electricity; in particular, it allows to determine whether or not the energy supplied is produced by RES.

IV. Proposed system architecture

As already introduced, to date one of the problems that afflicts the development of PEDs is the lack of management and certification systems that can help users to manage the energy exchanges inside the district and interface it with the power grid. A PED can be considered an aggregated virtual unit of both generation and load resources. Therefore, if managed optimally it can provide balancing or regulation services to the grid and be considered a new player in the energy market, even if to date the participation of PEDs in the energy market is not regulated. As for definition, the main purpose of a PED is to maximize self-consumption and ensure full utilization of RES in a way that doesn't generate GHG emissions and able to manage the flows of energy produced and any surplus. Achieving a balance between local energy production, energy efficiency, and energy flexibility is the driving goal of any PED. For this reason, in the evaluation of GHG emissions, it is also necessary to consider non-electric consumption such as heat production or mobility. The use of electric vehicles would allow for zero emissions due to traditional vehicles, but within a PED it has a great impact on the energy grid as the need for renewable energy generation increases significantly [38]. On the other hand, using electric vehicles to store surplus energy (smart charging) could significantly reduce the cost of distribution networks. In addition, they can be used as distributed storage across the territory for demand management to increase the flexibility of districts and also reduce the fluctuations of renewable energy generation.

It is clear that real-time monitoring and control play an important role in the management and proper operation of PEDs. Given the physical distribution of PEDs over the territory, management issues can no longer be efficiently addressed in a centralized environment, but rather require decentralized approaches and architectures. Over the last decade, the development of the Internet of Things (IoT) has enabled various equipment and devices to be connected in a distributed manner over the Internet to data analytics systems. IoT technology covers all the tools, systems, sensors, both hardware and software to support the deployment of IoT applications and devices. By means of IoT technology, common objects in a home can be made smart thus enabling the deployment of smart homes and likewise smart districts. IoT devices are the building blocks that enable the efficient development of a PED, enabling both the management and monitoring of electric vehicles, consumption, and both electrical and thermal energy resources.

In general, a PED, in addition to reducing GHG emissions, should be able to provide energy capacity to support the electric system. This results in the possibility of participation in Demand Side Management (DSM) programs with the purpose of avoiding grid faults, increasing the stability of the power system, reducing energy losses in grids and transformers, improving voltage quality, and postponing grid upgrades. DSM programs such as DR, are generally executed through virtual aggregation of users which makes their available capacity both decreasing and increasing. The aggregated unit is managed by an entity known as a Balancing Service Provider or aggregator, which receives modulation orders from the system operator in exchange for remuneration. Thinking about the structure of a PED, it is easy to note the analogy with the virtual units used for DR, but with the second purpose of optimizing self-consumption. In this way, the impact of the PED on the electrical system is twice, on the one hand the network is discharged, reducing losses and avoiding upgrading works, on the other hand the district is used to provide ancillary services, thus reducing peak loads and avoiding congestion. In addition, surplus energy can be traded with other nearby PEDs, thus generating a P2P energy market among PEDs and increasing the general energy efficiency of the power system. This mechanism could act as an incentive for users to constitute a PED as they can receive both profit from P2P energy trading and participation in DR programs. In general, what is needed for the full development of this new reality is a secure and transparent information system that allows the management, monitoring and control of PEDs. To this end, the use of new information technologies such as blockchain, in addition to providing a system for the certification of PEDs through the tracking of energy flows and their balance, would allow users to be identified on the blockchain as part of the PED, and the process of participation in energy services could be carried out through dedicated SCs. The blockchain would facilitate the aggregation of loads and generators that are part of the district, while also supporting the generation of the energy district itself.

The following fig. 2 shows the integration of a blockchain network in a PED.

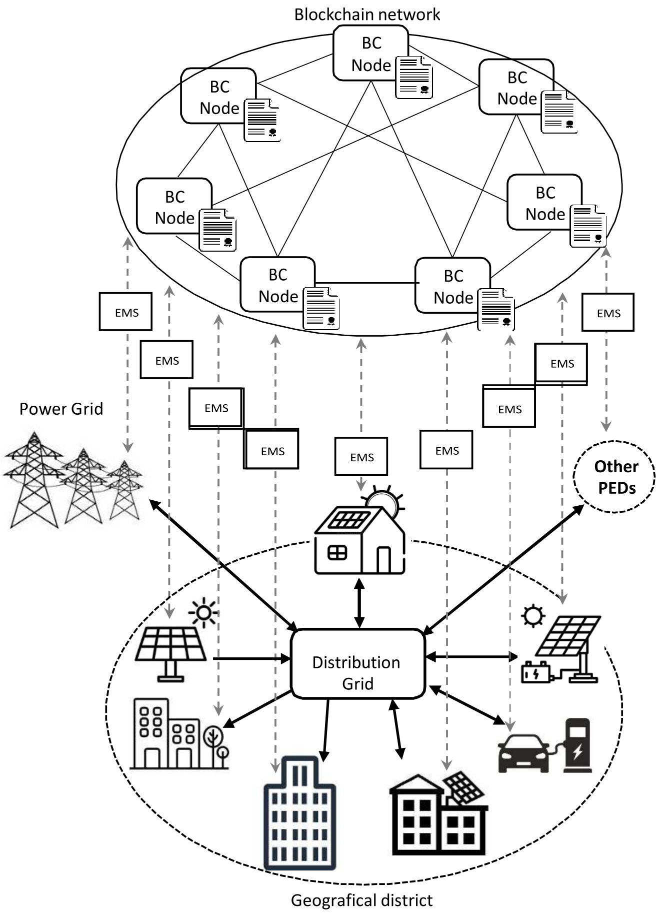

Fig. 2. Blockchain-based service overlay.

In order for users to interact with the blockchain, it is required a device that can interact with IoT devices and send/receive data from the blockchain. For this purpose, an Energy Management System (EMS) would allow to solve the problem. In particular, this device, if properly designed, in addition to sending data collected from IoT devices to the blockchain can receive commands given by the system manager and interact with local devices in order to better satisfy the requests and optimizing self-consumption. SCs running on blockchain nodes, in addition to implementing transaction logic, would enable certification of self-consumption and emissions reduction. The SC is executed every time a new transaction is sent to the network. Before the transaction is recorded on the ledger it must pass through the consensus mechanism for it to be considered trusted. Therefore, when a new transaction proposal is requested, it is processed by the SC of the node to which it was sent, if the response to the proposal is consistent with the logic implemented by the SC, the new transaction is sent to the other nodes that repeat the process. At this point, only if all the responses processed by the SCs running on the other nodes match, the new transaction is recorded in the ledger. This process enables unique and trusted certification of transactions. In the case of PEDs, transactions involve consumption and production data or energy flows between users and the network or other PEDs. Using EMSs, it is possible to automate the sending of this data to the blockchain, which will be processed and certified by SCs as described before. In this way, it is possible to certify the enrgetic positivity of the district and also the reduction of emissions.

V. Conclusion

The goal of PEDs, is not only ”net zero energy”, but to contribute to the realization of the energy transition and decarbonization of European energy systems. Urban areas cover a small part of the Earth’s surface, but are responsible for about 70-80% of global greenhouse gas emissions [39]. Air pollution and CO2 emissions in urban districts are mostly associated with combustion activities related to energy production as well as its use in the residential and transport sectors [40]. The emission sources of an urban district are not only energy-related, but are also related to transit and land use, household and workplace location. Reducing private transportation use and the availability and accessibility of public transportation are critical to mitigating the effects of land use land cover change-related emissions [41]. Another critical aspect of urban districts is waste disposal [42]. This offers a multitude of opportunities for converting waste to energy. Thermochemical treatments such as gasification, pyrolysis, and incineration, or biological treatments, may be potential methods to contribute to overall emission reductions.

New information technologies such as blockchain and the deployment of IoT devices for monitoring and managing both energy and not-energy resources can greatly contribute to the development of PEDs and certified tracking and assessment of GHG emissions. In this context, this work has proposed a blockchain architecture to be integrated into PEDs with the aim of providing an efficient, transparent and scalable digital tool for their optimal management and emission certification.

Acknowledgment

The authors wish to thank the SNAPP and the SMG labs at the Department of Engineering of the University of Palermo.

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