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Addressing Challenges in Prosumer-Based Microgrids With Blockchain and an IEC 61850-Based Communication Scheme

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ABSTRACT Since the advent of the microgrid (MG) concept, almost two decades ago, the energy sector has evolved from a centralized operational approach to a distributed generation paradigm challenged by the increasing number of distributed energy resources (DERs) mainly based on renewable energy. This has encouraged new business models and management strategies looking for a balance between energy generation and consumption, and promoting an efficient utilization of energy resources within MGs and minimizing costs for the market participants. In this context, this paper introduces an efficient management strategy, which is aimed at obtaining a fair division of costs billed by the utilities, without relying on a centralized utility or MG aggregator, through the design of a local event-based energy market within the MG. This event-driven MG energy market operates with blockchain (BC) technology based on smart contracts for electricity transactions to both guarantee veracity and immutability of the data and automate the transactions. The event-based energy market approach focuses on two of the design limitations of BC, namely the amount of information to be stored and the computational burden, which are significantly reduced while maintaining a high level of performance. Furthermore, the prosumer data is obtained by using IEC 61850 standard-based commands within the BC framework. By doing so, the system is compatible with any device irrespective of the manufacturer implementing the IEC 61850 standard. The advantages of this management approach are considerable for: MG participants, in terms of financial benefits; the MG itself, as it can operate more independently from the main grid; and the grid since the MG becomes less unpredictable due to the internal energy exchanges. The proposed strategy is validated on an experimental setup employing low-cost devices.

INDEX TERMS Blockchain, distributed generation, local energy market, prosumer, smart contract, Transactive Energy, aperiodic strategy.

NOMENCLATURE

Most of the symbols and notations used throughout this paper are defined below for quick reference. Others are defined following their first appearances, as needed.

A. ABBREVIATIONS & INDICES

MG	Microgrid
BC	Blockchain
SC	Smart Contract
EMS	Energy Management System
SBC	Single Board Computer
LD	Logical Device
LN	Logical Node
SoD	Send on Delta
SD	Standard Deviation
i	Index of prosumer of the Microgrid
t	Index of time
k	Index of aperiodic update

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B. PARAMETERS

$PV_i(t)$	PV power of prosumer i in the MG at instant t
$Demand_i(t)$	Inflexible demand of prosumer i in the MG at instant t
$Load_i(t)$	Controllable load of prosumer i in the MG at instant t
$Power_i(t)$	Balance of power of prosumer i in the MG at instant t
$Energy_i(t)$	Balance of energy of prosumer i in the last minute in the MG at instant t
$\rho_{MG}(t)$	Ratio between $PV_{MG}(t)$ and at $Demand_{MG}(t)$ at instant t
$\text{Price}_{buy}(t)$	Energy acquisition cost from the grid.
$\text{Price}_{sell}(t)$	Price offered by the grid for energy injection.
$\text{Price}_{MG}(t)$	Price of the energy in the MG.
$\text{Gap}_{price}(t)$	Price gap between buying and selling to the grid.
$\alpha_{price}(t)$	Price factor applied in the MG
$t_{i,k}$	Update time instant k of prosumer i.
Δ_{SoD}	Threshold Send on Delta.
$\text{Error}_i(t)$	Energy estimation error of prosumer i in the last minute at instant t.
$size_{round}$	Stored memory per market round.
$size_{tx}$	Stored memory per transaction.

I. INTRODUCTION

In recent years, the rapid expansion of Distributed Energy Resources (DERs), mainly based on renewable energy sources, has transformed the electrical power system resulting in reductions of greenhouse gas emissions and electricity costs, and mitigating adverse impacts on the power system such as overload on the main grid and transmission loss [1].

Increasing deployment of DERs which include some intelligence has changed the role traditional consumers play in the electrical power system, leading to a new actor that not only consumes but also produces electricity and maybe has demand response capabilities by means of some controllable loads and storage units [2]. This new actor in the electricity market is known as a prosumer that can be an energy provider or a consumer according to its local energy balance. Prosumers, as an entity, may consist of a combination of energy sources, loads, and storage capacity, and they seek to optimize economic decisions regarding their energy balance [3].

The integration of large amounts of prosumers, usually with low and unpredictable power generation capacity and electricity demand, is changing the traditional approach of power systems, which is posing new challenges [4], and creating new opportunities for the generation and distribution operators and for the electricity market. The traditional centralized concept of the grid has given way to a complete decentralized strategy where several prosumers are interconnected and locally managed being seen by the utility grid as a controllable load or generator. Microgrids (MGs) epitomize this concept, which was first introduced in [5]. MGs facilitate the integration of DERs, without compromising the resilience of the main grid, creating opportunities for new economic models such as electricity trading, which can take place not only between MGs and utilities, but also among multiple prosumers, through a local energy market. They also promote the development of control systems that allow plug & play capabilities to face the ever-changing MG architecture.

This new concept, which challenges also the traditional business models, required a comprehensive framework with the aim of determining the electricity prices and defining the new business players and models, such as peer-to-peer frameworks for locally energy trading and transactions. In this context, prosumers try to maximize their profit by selling their surplus energy and the grid aims at maximizing efficiency.

To address these challenges, several works can be found in the literature proposing different solutions mainly based on centralized and distributed energy management systems (EMSs). Regarding the former, in [6] and [7] MGs are considered as scaled-down versions of the centralized electricity system and the EMS is defined accordingly. Centralized MG management and control suffers from drawbacks in terms of: (a) the need for a MG central controller with high computational capabilities, due to the amount of controllable resources, (b) lack of scalability since a small change in one node affects the central controller; and (c) privacy [8] as customers may not be willing to share their private data. Finally, all the information must be integrated and processed at a single point, which also results in reliability and security vulnerability of the central controller [9].

To overcome the drawbacks of the centralized methods, new EMS designs have been developed in a distributed fashion. For instance, in [10] authors simulate a MG with a distributed EMS achieving comparable performance with respect to the centralized counterpart. In [8] an example of distributed EMS, which includes a MG central controller (MGCC) operating in conjunction with the local controllers, is presented. However, this combined approach does not eliminate the vulnerability of a single point of failure.

The creation of local energy markets, that allow consumers and prosumers to trade energy, has been studied in the literature [11] as a way of decentralized management in MG. In local energy markets, prosumers try to match supply and demand by seeking competitive electricity prices, which results in greater resilience. The Brooklyn Microgrid [6] is one of the most known projects for the implementation of MG local energy market, which confirms the economic and technical feasibility of decentralized strategies. In [12], the concept of local energy market is taken one step further by interconnecting several geographically close MGs, which allows the surplus and deficit of energy to be exchanged in a neighboring market. This further reduces the dependency on the main grid and, as a result, increases the resilience of the MGs.

This paper introduces a novel event-based local energy management strategy for MGs. The design, development and implementation of the strategy is based on the combination of the BC technology and the IEC 61850 communication standard, enhancing the capabilities of both technologies when applied to energy-sector applications. BC technology is used to create a local energy market in a decentralized fashion, which has been proved to be remarkably resilient to failure and cannot be maliciously manipulated as it maintains a detailed record of past transactions that cannot be changed retrospectively. Furthermore, executable code embedded in the BC, which is called the smart contract (SC), allows the entire process to be automated [13]. Likewise, the BC-based local energy market is standardized by using the IEC 61850 communication protocol. The strong point of this approach is that the electrical parameters of all MG resources can be automatically obtained without the involvement of the resource owners, which avoids manipulation of those parameters for their own advantage. To the best of the author's knowledge, this is the first local energy market implementation that combines the IEC 61850 and BC technology whereby devices commercialized by diverse manufacturers can be seamlessly integrated in the market, in a plug & play fashion, which approaches to a real project. Research works in this topic are non-existent.

The main contributions of this paper are summarized as follows:

1. Integration of the IEC 61850 standard into the Smart Contracts of the BC. This enables the distributed communication between the commercial devices implementing the standard.
2. A reduction in the amount of resources required to create a local distributed energy market by means of event-based techniques which do not negatively affect the system performance. This allows the system to operate efficiently for a greater number of years.
3. Low-cost hardware implementation of the system, which decreases the time for the return on the investment making it feasible to use it in residential environments.
4. For both energy producers and consumers, the development of a win-win market strategy within the MG allows financial savings to be obtained by taking advantage of the gap between the price paid for the electricity consumed and that generated and injected to the grid.

The paper is organized as follows: Section II describes the underlying technologies employed in the local energy market design, namely BC and IEC 61850 communication standard and the advantages that they can bring to the energy sector in general and to MGs in particular. Section III shows the advantages of the combination of both technologies. Section IV describes the design of proposed prosumer-based microgrid. Section V presents the implementation of the proposed BC-IEC 61850 network, analysing the required resources for its correct operation. In section VI, the system is tested in a specific case of use. Finally, in Section VII, the conclusions and the future work are outlined.

II. LITERATURE REVIEW: STATE OF THE UNDERLYING TECHNOLOGIES

Vast literature has been published on BC technology and IEC 61850 communication standard separately. However, the literature lacks references considering both technologies working together. This paper aims at filling this gap. In this section a literature review of the two technologies mentioned above, is carried out. Being two of the most researched technologies and with the aim of narrowing the search, this section only deals with the most recent and up to date works in the context of the energy sector and MG.

A. BLOCKCHAIN TECHNOLOGY IN MICROGRIDS

BC is the technology behind Bitcoin cryptocurrency, created in 2008 by Shatoshi Nakamoto [14]. This disruptive technology is based on decentralized computation with secure storage and transactions. BC has evolved since then, and these days, BC is being widely used in fields, such as, transportation systems [7], IoT [8], financial sector [9], electric vehicle charging and e-mobility [10], and the energy sector in general [15], inter alia.

BC can be briefly defined as a decentralized information network with a distributed computing paradigm, which means that there is not a master computer compiling and processing the information. BC is based on a distributed ledger which guarantees the immutability of stored data and the availability of the latest version in each node of the network. To that end, BC employs chronological, chained blocks to store encrypted data generated by distributed consensus algorithms. Therefore, blocks record transactions, i.e. actions created by the BC participants, and ensure that they are in the correct sequence and have not been tampered with. This is achieved by linking each new block with all the previous ones through an ID that is unique and dependent on the information contained in the block and the ID of the previous block. This allows any change in the information contained in the previous block to be quickly detected and discarded. Thus, this technology makes it possible to eliminate intermediaries making all the transactions faster and more secure, as previous records cannot be altered, and they are available at any time for all the participants in the network. In 2014 the BC technology rapidly evolved with the creation of a new cryptocurrency, Ethereum [13], which allowed code to be executed in a decentralized way via the so-called Smart Contracts.

BC solutions for the energy sector have been proposed in several works. A comprehensive review of BC activities and initiatives in the shape of projects and startups in the energy sector can be found in [15]. The authors argue that the decentralized features of BC technology facilitate the creation of trading platforms for billing purposes. They also include an extensive survey of platforms used to design projects in the energy sector. In [12], a review of BC-based current projects and platforms in different domains is carried out. They determine the requirements of smart energy systems with the aim of identifying appropriate BC-based solutions for smart energy applications. In [6] a case study proves the effectiveness of BC when it comes to operating decentralized MG energy markets. The authors in [16] go beyond economic aspects of energy transactions and, by means of BC technology, they track energy losses during energy transactions in MGs.

Distributed Generation, MGs and the implementation of energy local markets for energy trading call for the use of BC technology. This will, without doubt, transform the energy landscape as shown in the literature where numerous projects under development or in preliminary testing are presented.

B. COMMUNICATIONS STANDARDS: IEC 61850 IN MICROGRIDS

The IEC 61850-based communication standard has been universally accepted for substation automation [17]. However, new parts have been developed and published allowing the standard to be used as a standard for communication networks and systems for power utility automation. Most researchers agree that the future trends are towards standardization through IEC 61850 since it is based on the interoperability approach.

In the context of MGs, efficient and secure communications among all the nodes become an essential feature. This is another ongoing research topic as demonstrated by the numerous papers recently published in the literature. In [18] an IEC 61850-based energy management system for emergencies is presented. The paper shows the plug-and-play capabilities that the IEC 61850 standard can bring, for alternative power system operation based on local assets in the event of an emergency. A review on the evolution of MG communication approaches is presented in [19], where authors identify specific communication requirements in MGs such as reliability, scalability, interoperability and cybersecurity, which can be fulfilled by the help of the IEC 61850 standard. An IEC 61850-based model of a MG protection system with logical nodes and datasets is proposed in [20] which is aimed at ensuring the protection in a bidirectional system. In [21] authors propose a standardized communication framework based on IEC 61850 to manage energy routers and to improve the operation of MGs achieving the optimal selection of the power source and routing path. Communications for management and control of MGs based on IEC 61850 are designed and implemented in [22] and [23], proving the effectiveness and security of the standard when implemented in a distributed EMS with small end-to-end latency times within WAN networks. Finally, in [24] IEC 61850 is also used to improve MG automation, proposing a standard-based model for controllable loads. Results from the above research works encourage and support the inclusion of IEC 61850 in MG management and automation.

In 2009, in response to the increasing number of DERs aggregated to the grid, part 7-420 [25] was provided, which standardizes several DERs by using predefined logical nodes (LNs). Device modelling via LNs helps to simplify the integration of equipment from different manufacturers. This significantly facilitates the implementation, as well as the interconnection of different MGs.

III. HIGHLIGHTS OF THE COMBINED APPROACH

This section highlights the benefits of combining BC technology and the IEC 61850 communication standard in MGs.

As stated above, BC technology has prominent features, such as immutability of the stored data, decentralization, public ledger facility and security, to name a few. These inherent features have promoted the use of BC technology to overcome the main drawbacks of centralized-based EMSs for MGs. Despite of the obvious benefits derived from the use of BC technology, there are, however, potential shortcomings and challenges which stem from the fact that BC is far from being a mature technology in MG applications [26], [27].

These shortcomings are especially relevant in Prosumer-based MGs. These MGs are dynamic in nature, where prosumers join or leave the MG. Therefore, the MG changes its temporal and spatial topology, which poses a challenge. To face this problem, the proposed BC-IEC 61850 strategy presents the following features:

1.-Interoperability: equipment and hardware used in MGs are usually manufactured by different vendors overlooking the interoperability between these devices. This aspect plays an important role in producing standardized transactions for the BC implementation.

2.-Generic plug & play: The design of non-device-specific SCs provides the capability to add or remove different commercial devices from the MG, introducing the switches automatically to the local energy market.

3.-Veracity: Data acquisition in a distributed manner by running SC with IEC 61850 communication standard adds an extra layer of security as it reduces the chances of manipulation with respect to data acquisition locally and subsequent delivery for storage in the BC.

IV. DESIGN OF THE PROSUMER-BASED MICROGRID

In this section, the proposed prosumer-based architecture for a MG is introduced. The developed strategy takes advantage of the fact that prosumers generally have different energy demand and supply profiles which depend on the prosumers' energy generation capacity, or whether they have energy storage systems (ESSs) or some controllable loads. This means that prosumers could draw or inject electricity into the distribution grid at different times and in different quantities for profit maximization.

The proposed architecture relies on energy agents representing prosumers within the MG, which are interconnected through their own distribution grid. The MG is connected to the main grid at a single point, through a point of common coupling, where the amount of energy is measured by bidirectional smart meters. As the electricity prices vary substantially over the day, splitting the cost of the bill among prosumers is not straightforward. Local energy markets arise as a means of overcoming the problem of fair cost sharing, and

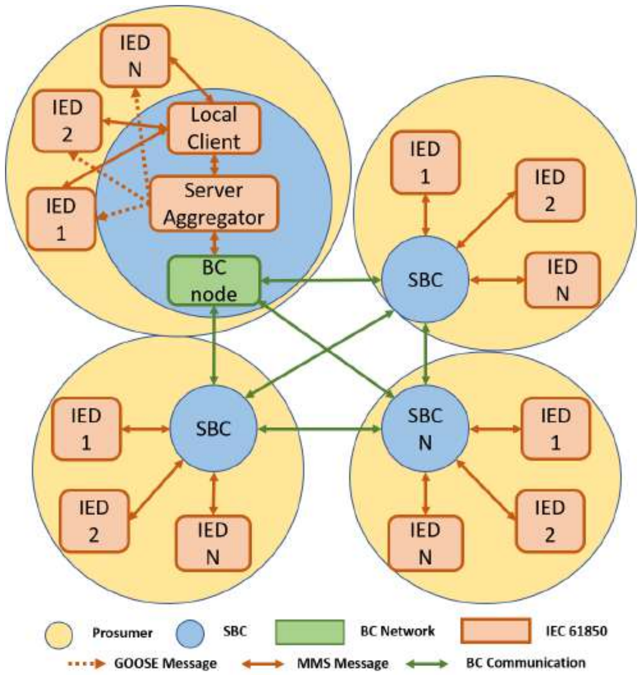

FIGURE 1. BC-IEC 61850-based communication architecture between the different devices that comprise the MG.

balancing energy consumption and generation curves within the MG, thereby reducing the amount of energy exchanged with the main grid.

The objective of the proposed MG is to facilitate the deployment of clean energy technologies, while eliminating the potential barrier to achieving fair cost sharing. To address this, the designed market strategy increases the return on investment by providing cost savings and increasing profits e.g. reducing the electricity bill, trading energy surplus, etc., for the prosumers participating in the MG. Finally, the privacy and veracity of the prosumers' data are guaranteed by combining BC technology and the IEC 61850 communication standard.

A. COMMUNICATIONS ARCHITECTURE BASED ON BC AND IEC 61850

In this section, the communication architecture based on BC and the IEC 61850 standard for the proposed prosumer-based MG is described. It is assumed that the prosumer's installed equipment, i.e. inverters, energy storage elements, smart meters, controllable switches, etc., complies with the IEC 61850 standard. The IEC 61850 communication standard works with a client-server structure in which Intelligent Electronic Devices (IEDs) play the role of a server. The servers send their data by request of the client. Therefore, an IEC 61850 client is only needed to collect data from these servers.

FIGURE 1 shows the architecture that implements the communications between the MG prosumers, and combines BC technology and the IEC 61850 standard. It can be seen that prosumers are connected to each other through a BC network. The installed equipment for each prosumer consists of two types of devices: the IEDs, which are IEC 61850 servers, and a single board computer (SBC) which comprises a standard client, a standard server with the installation model and a BC node. The messages exchanged between clients and servers are based on the Manufacturing Message Specification (MMS) protocol whereas those sent by the server aggregator to the IEDs are based on Generic Object-Oriented Substation events (GOOSE) with the aim of minimising the latency in the installation's state changes. Both protocols are based on the IEC 61850 standard. GOOSE messages are directly transmitted through ethernet packets with a subscriber-publisher structure and with a maximum latency of 3 ms [28].

The standard IEC-61850 operation is implemented in the Prosumer Local Phase (described in detail in SECTION IV-B-1) in which a client, which runs on a SBC, constantly reads the prosumer's IED data. This local client sends the data to a server aggregator. The proposed aggregator is modelled according to the Smart Home System proposal [17], in which the SHCT logical node is presented. This node is based in the IEC-61850 standard and is aimed at: (i) controlling the installation as a whole (the amount of energy exchanged with the network and the price of such exchanges); (ii) switching to the different modes of operation, i.e. islanded or grid connected; and (iii) defining optional configurations (voltage and current limits, times at which different operating modes are allowed, etc.).

The implementation of another IEC 61850 client in the form of SC can be considered as a novel feature of the proposed system. The execution of this SC results in the acquisition of data from all aggregator servers that are connected to the MG. This execution occurs automatically whenever an aggregator detects that the conditions of the installed equipment have changed significantly since the last acquisition.

This SC sends an MMS message to each of the registered devices and, in response, it receives another MMS message with the requested data. From this data only those parameters affecting the efficient system operation, e.g. energy generation-consumption balance in the time period since the last BC register update and the current demand, are included in the BC immutable database. Furthermore, if the prosumer has additional generation capacity or conversely load demand through controllable loads, it sends an offer of the amount of extra energy it can provide or absorb from the MG.

In this way it is verified that the SC is designed to read any IED from any manufacturer that supports the IEC 61850 standard, acquiring the selected parameters. Moreover, the results of the local energy market are sent to each SBC through an MMS message by executing another SC, which acts as IEC 61850-based client updating the data of the server aggregator. If the server aggregator receives an order to change the state of the installed equipment, the aggregator sends GOOSE messages to all the IEDs needed to make this change possible, at a given instant of time.

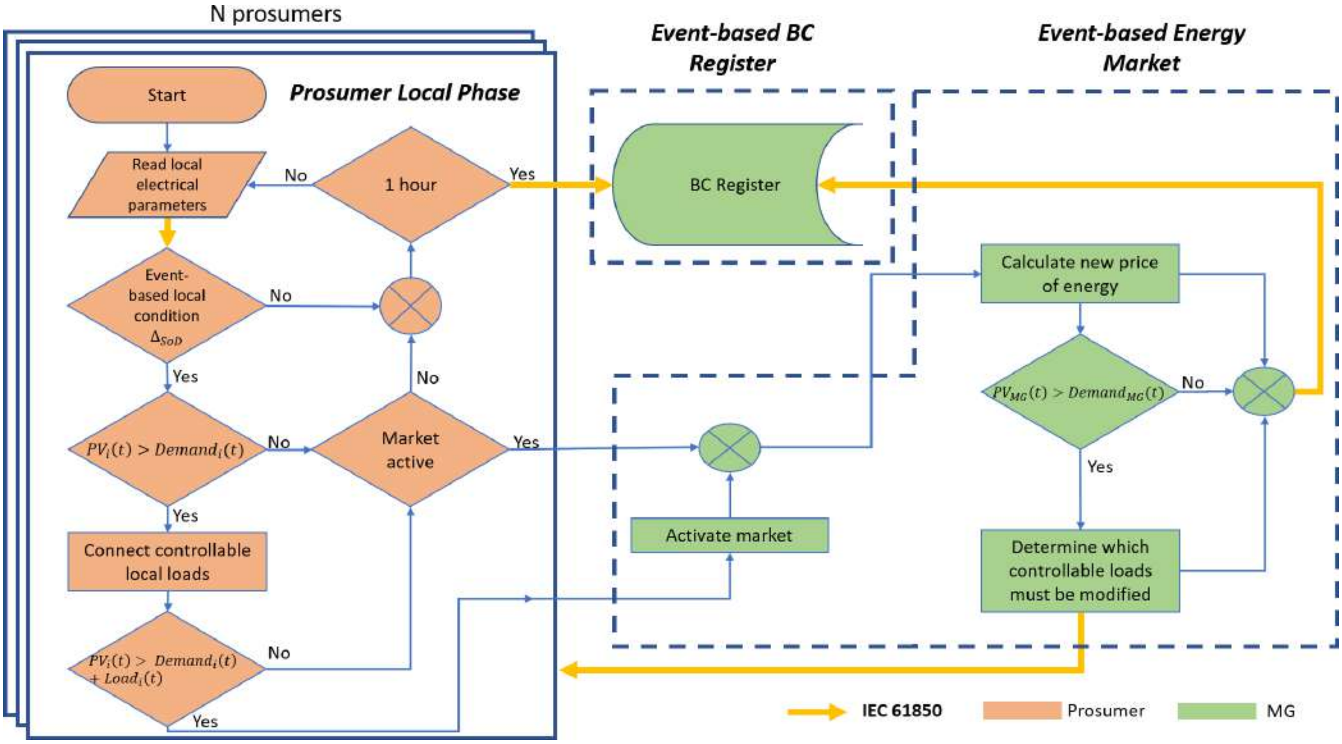

FIGURE 2. Flowchart representing the tasks prosumers perform both locally in a distributed manner through the SC. Three phases are clearly differentiated: prosumer local phase, event-based energy market and event-based BC register.

B. EVENT-BASED LOCAL ENERGY MARKET

BC technology relies on an ever-growing distributed database, which is updated by appending blocks containing new information. These blocks are sequentially attached to the end of a file which compiles all the information that was previously received. As a result, the amount of information to be stored and transmitted becomes one of the most critical parameters when it comes to designing a hardware system to implement the BC.

To meet this challenge and to reduce the communication within the MG, an event-based local energy market is designed. This event-driven control approach triggers the market only when there is a significant change in the energy exchanges within the MG. Consequently, a significant reduction in the amount of information to be processed and sent through the communication channels is achieved, without degrading the system performance. For its operation, a Send on Delta (SoD) data collecting scheme is chosen for its simplicity and efficiency [29]. At the prosumer level, an implementation of SoD monitoring strategy evaluates the difference between the last-minute energy measurement sent by the prosumer to the MG and the current measurement. When the value of this difference is above a certain threshold level, Δ_{SoD}, which is set by the designer, the local energy market must be updated.

The expression used to calculate the difference mentioned before is the following:

$$t_{i,k} = \min\{t > t_{i,k-1} \| Energy_i(t) - Energy_i(t_{i,k-1})| \geq \Delta_{SoD}\}, \quad (1)$$

with:

$$Energy_i(t) = \int_t^{t+\Delta_t} Power_i(t)\,dt, \quad (2)$$

$$Power_i(t) = PV_i(t) - Demand_i(t) - Load_i(t), \quad (3)$$

$$\Delta_t = 60s, \quad (4)$$

where $t_{i,k}$, represents the trigger instant of the prosumer i, $Demand_i$ and $Load_i$ are the non-controllable and controllable load demanded by prosumer i, respectively, PV_i is photovoltaic energy generated by prosumer i, $Power_i$ indicates the power balance of prosumer i, $Energy_i(t)$ is the last minute energy of the prosumer with respect to instant t in kWh and Δ_t, is the integration time.

The local trigger of any prosumer leads to a new market update, thus the market is always distributed and executed locally to fulfill the decentralized nature of BC technology. The operation of the proposed event-based local market is described in detail in the flow chart shown in FIGURE 2. This flowchart depicts the main tasks of the proposed strategy. The tasks are carried out in three phases:

1) PROSUMER LOCAL PHASE

The local phase of each prosumer relies on the use of the IEC 61850 communication standard to send the electrical parameters to the MG. Firstly, each prosumer's SBC locally monitors its electrical parameters through IEC 61850-based messages. Through a Manufacturing Message Specification (MMS) protocol for IEDs, changes in the prosumers' energy balance, i.e. changes greater than the aperiodic update threshold Δ_{SoD}, are detected. Whenever the prosumer satisfies the triggering condition, it is checked whether it is generating more energy than that consumed. To activate the prosumer's controllable loads, a GOOSE message is sent by the aggregator, because GOOSE messages are significantly faster than MMS messages. If the prosumer's energy balance is still positive, the local energy market is activated by executing a SC that captures the electrical parameters of all the prosumers within the MG in a distributed manner. In addition, the SC is also randomly executed by one of the prosumers on an hourly basis, even though the trigger condition is not satisfied. By doing so, a record of all the prosumers' electrical parameters is stored in the BC, with a dual purpose: firstly, the current MG state is known beforehand; and secondly the record saved is used for checking and splitting the billing.

2) EVENT-BASED ENERGY MARKET

The market phase begins when at least one of the prosumers has a positive energy balance in that instant of time, i.e., the prosumer generates more energy than it consumes at that point in time. The first step in this phase consists in calculating the price of the energy to be exchanged in the period considered as detailed in section IV-C In a second step, it is checked whether the energy the prosumers are injecting into the MG is greater than that being consumed. If this is the case, each prosumer with available controllable loads, submits an offer with the aim of taking advantage of more economically competitive energy. The MG matches the offers received for the energy surplus generated and sends the offer matching results to the prosumers so that they can control the loads based on those results. This is done by sending an IEC 61850-based message to their IEDs following the MMS protocol. The process of offer matching takes into account the current state of the controllable loads, which in the case of energy storage elements aims at equalizing the energy levels stored by all the prosumers that comprise the MG.

3) EVENT-BASED BC REGISTER

In this last phase, at the given time points defined by the two previously described phases, all the electrical parameters obtained through the IEC 61850 communication standard, the values of the energy exchanged between the different prosumers and the corresponding prices, are registered in an aperiodic fashion in the BC. In this way, the prosumers' bills for the energy drawn from the grid can be calculated by considering the price reduction and increase that each prosumer has to pay for the energy exchanges within the MG.

C. LOCAL ENERGY MARKET STRATEGY

This section describes the developed local energy market strategy. It is important to know that in most conventional trading schemes, prosumers have virtually no control of the trading process of the electricity they generate. Utilities buy and sell energy to retail prosumers by applying a profit margin and a set of taxes and surcharges. This results in a significant difference between the electricity prices paid to the prosumer for the electricity injected into the grid and that paid to purchase electricity from the grid [30]. Since the MG is made up of prosumers that want to purchase and sell energy at different times, the proposed local energy market offers more competitive energy purchase and selling prices than those of the utilities. Local energy markets are, therefore, beneficial to their participants provided that the average electricity price is lower than that set by the main grid.

The proposed market strategy takes advantage of the price difference between the purchase and sale price of energy to the grid. The pricing mechanism is based on matching the purchase and selling offers made by the prosumers for an amount of energy when the event-based market is activated, as described in section IV-B. When the market is activated and the information sent by all the prosumers is available, the amount of energy delivered and demanded within the MG is calculated as follows:

$$Demand_{MG}(t) = \sum\nolimits_{i=1}^{N} Demand_i(t), \tag{5}$$

$$PV_{MG}(t) = \sum\nolimits_{i=1}^{N} PV_i(t), \tag{6}$$

where N is the number of prosumers in the MG. With this data, the price of energy in MG is calculated for the amount of energy available to be exchanged. The market price is set by the following formula:

$$\text{Price}_{MG}(t) = \text{Price}_{sell}(t) + \alpha_{price}(t) * \text{Gap}_{price}(t) \tag{7}$$

with:

$$\text{Gap}_{price}(t) = (\text{Price}_{buy}(t) - \text{Price}_{sell}(t)) \tag{8}$$

$$\alpha_{price}(t) = \begin{cases} (0.5 - 0.2\rho_{MG}(t)), & \rho_{MG}(t) < 1 \\ 0.3, & \rho_{MG}(t) \geq 1 \end{cases} \tag{9}$$

$$\rho_{MG}(t) = \frac{PV_{MG}(t) - Demand_{MG}(t)}{Demand_{MG}(t)} \tag{10}$$

where ρ_{MG} represents the value of the energy ratio between the PV energy and the demand in the MG. α_{price}, represents the price adjustment factor within the MG. For values of ρ_{MG} greater than or equal to 1, this factor is adjusted to 0.3 to set a minimum factor within the MG. Gap_{price} represents the difference in price between buying (Price_{buy}) and selling (Price_{sell}) to the grid. Finally, $\text{Price}_{MG}(t)$, indicates the price of the surplus PV energy of prosumers that are purchased by other prosumers within the MG.

Through this formula a win-to-win market strategy is established for all prosumers due to the fact that prices within the MG will include the sale price to the grid plus a part of the Gap_{price} which will vary between 30% and 70% depending on the energy ratio ρ_{MG}.

Once the price is set, the surplus PV power is assigned to all the non-controllable loads of the MG. In case the surplus is not enough for all the loads, it covers the same percentage of each one of them and the rest of the demanded energy is consumed from the grid. In this way, each prosumer has a part of the energy at market price and another part at the grid price.

On the other hand, if the surplus is greater than the non-controllable loads, the transactions with the controllable loads are established, proceeding to activate them as indicated in FIGURE 2. In this case, all the possible loads are activated, giving priority to the prosumers that have the greatest capacity remaining to be fed.

Finally, if all the available controllable loads are fed and there is still a surplus power, it will be injected into the main grid. In this case, the energy not consumed in the MG is sold at the grid price, the percentage of surplus energy injected to the grid is calculated and this percentage is applied to the benefit of each prosumer that is injecting at that moment. This way, all prosumers with surplus will have the same percentage of their power injected at MG price and the rest at grid price.

V. IMPLEMENTATION AND PERFORMANCE EVALUATION OF BLOCKCHAIN-IEC 61850 PROPOSAL

To promote the use of renewable energies, the proposed strategy improves the operation of MG, maximizing the benefit of all its participants. To this end, it is essential that both the initial investment and the operational cost of the system are as low as possible. Consequently, to bring down the cost associated with the operation of the hardware system, low-power consumption strategies are mandatory. Therefore, consensus algorithms such as Proof of Work (PoW) [31] cannot be used, since appending new blocks in the BC demands high computational power, e.g. a node must decipher a cryptographic puzzle, which drives up the cost of the hardware implementing the node and increases energy consumption.

To select the most suitable technology for the BC introduced in this paper, a comprehensive review of the available frameworks to implement BC technology has been conducted. In [15] the underlying technologies employed in 140 projects that integrate BC technology in the energy sector are analyzed in detail. For the purposes of this work, the Hyperledger Fabric [32] is the best option for several reasons, namely: (a) it allows BC networks to be created in which each prosumer must be registered to participate; (b) the consensus algorithm is based on Byzantine Fault Tolerant protocols i.e. if there is a fault in any of the nodes of the BC network, it can continue operating without any problem; and most importantly (c) this framework is open source, which means that the code is available and can be modified and adapted to implement new functionalities. This significant advantage allows ARM-based hardware architectures to be included for BC implementation. This feature, which is not included in the original framework, allows the range of potential hardware components to be extended thereby reducing the cost and the power consumption of the final system.

A. HARDWARE IMPLEMENTATION

The hardware implementation of the BC network is based on the Raspberry Pi 4 model B [33], one of the most popular SBC. The selection is based on comparing performance characteristics through numerous benchmarks which are used to measure the millions of operations per second (MOPS) the hardware architecture can perform. Furthermore, the performance evaluation can be extrapolated to other architectures. In [34], an extensive set of tests are performed on the Raspberry Pi.

B. HYPERLEDGER FABRIC

The modular architecture of the Hyperledger Fabric framework [32] makes it possible to implement the energy exchange system in three phases:

1. The first one consists in building Hyperledger Fabric Docker images targeted towards hardware architectures with the 64-bit ARM processor such as Raspberry Pi devices. In addition, these docker images are modified to integrate the libiec61850 library [35], required for the execution of IEC 61850-based clients into the images. By doing so, the library can be used in the SCs. These modified images are freely available for download 36].
2. The second phase deals with the process of writing SC in Go language. Hyperledger Fabric supports Smart Contracts authored in general-purpose languages such as Java, Go and Node.js. However, among those languages, Go allows the use of the most complete and updated library for the IEC 61850 standard implementation, the libiec61850 [35], written in C language.
3. Finally, in the last phase, the clients interacting with the blockchain, are specified in JavaScript. These programs control the execution of the SCs.

In the Hyperledger Fabric framework, due to its modular architecture, every node in the system can be individually modelled displaying unique characteristics. However, in this work, the nodes comprising the blockchain have been designed to share the same characteristics thereby achieving a set of nodes with no priority over each other. Docker images of peer, those of orderer and an external database called CouchDB [37] have been integrated, to be able to submit enriched queries, which facilitates the development of applications that make use of the stored data.

C. PERFORMANCE EVALUATION

To assess the performance of the approach presented in this paper, a BC use case is tested, in which the market rounds happen at five-minute intervals. At the beginning of each market round, the prosumers send an offer in terms of the energy they need or the energy surplus they have. Then, to match the offers, a SC is executed, whereby it is determined whether a particular prosumer has to inject or draw energy from the grid. Finally, another SC is executed to read, in a distributed way, the IEC 61850 compatible devices and to save the data representing the state of the devices during the interval of time in the BC. By studying the data collected from the previous use case, the results can be extrapolated to other time intervals for the market rounds. Tests have also been carried out for different number of prosumers with the aim of evaluating the BC-IEC 61850 performance based on the number of prosumers that make up the MG. With the information

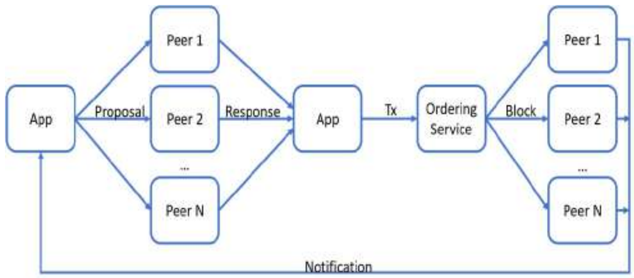

FIGURE 3. Transaction flow in Hyperledger Fabric framework.

compiled by running the tests, the required resources for the docker containers making up the nodes (peer, orderer and CouchDB), in terms of CPU usage, bandwidth, required storage and latencies are individually evaluated. This allows prosumers to assess whether to integrate an orderer or just the peer in their hardware devices reducing the cost of the system at the expense of affecting performance.

1) HYPERLEDGER FABRIC TRANSACTION FLOW

To gain a better insight into the data obtained, FIGURE 3 schematically shows the flow of information exchange involved in each transaction for it to be included in the BC. More detailed information can be found in [32]. From the figure, it can be seen that, the client application sends to all the SBCs working as peers, a transaction proposal created by the Hyperledger Fabric SDK. According to the endorsement policy that has been established, a subset of peers has to verify that the transaction is valid. In other words, each transaction needs only to be endorsed by the subset of peers required to satisfy the transaction's endorsement policy. For the transaction to be valid, the following points must be proved: (a) the proposal must be well formed; (b) a similar proposal must not have been completed in the past; (c) the signature must be valid; and (d) the client requesting the transaction is authorized to do so.

If the endorsement policy has been satisfied, the client application submits the transaction to the ordering service, which establishes consensus on the order of transactions and creates transaction blocks. A block can be created either when a predefined period, from the arrival of the first transaction, has elapsed or when the maximum number of transactions, the block can contain, has been reached. Once the block is created, the ordering service is responsible for broadcasting it to each peer, which append it to the end of their BC. When the ledger is up to date, a notification is sent to the client application informing it that the transaction has been correctly processed or that an error has occurred.

2) CPU

The total CPU usage, which is given by the percentage of use of one Raspberry Pi core, has been calculated considering the individual CPU utilization of the docker containers making up a BC node. This allows the analysis of the required resources to be more precise. TABLE 1 shows the minimum and maximum values of the CPU usage for the tests carried out for each element.

TABLE 1. Minimum and maximum CPU utilization in each test performed by each docker container.

Number of nodes	Peer		Orderer		CouchDB	
	Min (%)	Max (%)	Min (%)	Max (%)	Min (%)	Max (%)
3	1,73	2,22	0,23	0,89	0,69	2,43
4	2,30	2,94	0,22	1,07	0,68	1,91
8	2,36	4,53	0,15	0,59	0,62	2,29
16	3,40	6,60	0,24	0,93	0,63	2,49

TABLE 2. Bandwidth needed for the peer and the orderer as a function of the number of nodes that make up the BC network.

Number of nodes	Peer		Orderer	
	TX	RX	TX	RX
3	34,22	40,29	37,37	16,00
4	64,69	67,57	62,12	21,17
8	111,40	163,30	85,26	40,07
16	192,60	236,30	163,50	65,92

As for the peers, the maximum CPU usage follows a logarithmic trend as a function of the nodes connected to the BC. On the other hand, as far as the orderers are concerned, the CPU utilization changes slightly as the number of nodes increases, ranging from 0.15% to 1.07%. The CPU usage by the external database exhibits similar behavior with values ranging from 0.69% to 2.49% irrespective of the number of nodes.

For the worst-case scenario, with a 16-node blockchain and considering the maximum values of CPU time consumed by the elements that comprise the node, the CPU usage ratio just for one core of the 4-core processor, is roughly 9.16%. Therefore, it can be concluded that the hardware architecture comfortably meets the computational requirements of the system, again irrespective of the number of nodes.

3) BANDWIDTH

A similar procedure to that described above, has been followed to determine the bandwidth for the effective operation of the system. In contrast to the CPU usage, peak values for the bandwidth occur when transactions take place, when the nodes communicate with each other to validate the transactions, when they are accepted by the BC, and when the nodes are synchronized with the latest transactions.

As an example, FIGURE 4 shows the required bandwidth for both sending and receiving data by every peer and orderer in a 4-node experimental test. It can be observed that a peak occurs during the insertion of offers by prosumers. Likewise, a half-period-delayed smaller peak can also be

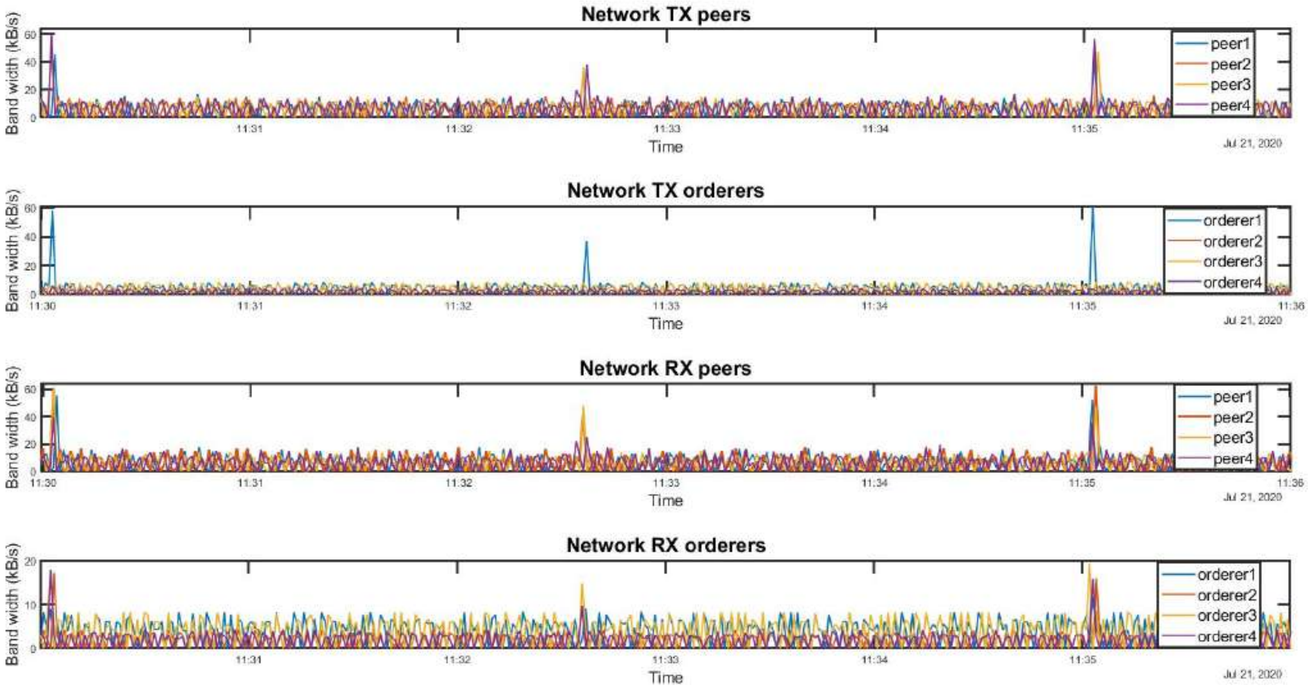

FIGURE 4. Bandwidth required by the peer and the orderer for both sending and receiving data in the test performed with four nodes. Every 5 minutes all the users send an offer to the market and in the middle of the period two transactions are made, collecting the data from the IEC 61850 server and matching the offers.

seen, which corresponds to the process of offer matching and that of reading the prosumers' IEC 61850 compatible devices. The magnitude of the peak values for the bandwidth varies according to the number of nodes making up the system (see TABLE 2). For the 16-node network, i.e. the worst-case scenario, the maximum bandwidth measured for uploading and downloading has been 356 kB/s and 302kB/s, respectively.

4) REQUIRED STORAGE

The data size in the BC becomes an important parameter which depends on the structure of the blocks in the Hyperledger Fabric framework [38]. The blocks consist of a header, a body which is composed of a variable number of transactions and the block metadata.

The number of transactions within a block depends on two factors, the maximum number of transactions the block can contain and the waiting time from the arrival of the first transaction until the block is formed. The number of transactions per block has been limited to 10 in this work because this way the best performance is achieved [38]. The timeout has been set at 1 second since no minor latencies are required for the correct operation of the system and the more transactions that enter the same block, the less storage required. Every transaction has three parts when it comes to creating a block: (i) the transaction proposal sent by a peer to endorsing peers; (ii) the transaction validation by the endorsing peers; and (iii) the response to the requested transaction by the smart contract invoked.

The block size has been determined through experiments on the 16-node blockchain where most of the nodes must verify the transaction before acceptance. Measurements revealed a block size ranging from 4 kB for one transaction to 32 kB for ten transactions.

Each SC execution is considered as a transaction. Therefore, there are four blocks with only one transaction in each round: (i) the electrical parameters are registered; (ii) the market is started (iii) the price is calculated; and (iv) offers are matched and the results are sent. In addition, users interested in buying or selling energy on the market send an offer (by the execution of another SC) simultaneously. This creates new blocks with a size between 1 and 10 transactions each.

Since the information contained in a transaction (alphanumeric data only) is small compared to the total size of the block, it can be assumed that all transactions in the system are of a similar size regardless of the transaction. Therefore, the storage required by the execution of a market round can be estimated with the following formula:

$$size_{round} = 4 \cdot size_{tx(MAX)} + size_{tx} \cdot N \tag{11}$$

where $size_{round}$ is the storage that is needed in a market round, $size_{tx(MAX)}$ is the storage required by a block with a single transaction, $size_{tx}$ the average storage used by a transaction in a block with several transactions and N the number of prosumers in the MG.

It is considered that the endorsement policy (section V-C-1) is fixed in a subset of 16 peers. Consequently, the size of the block is not increased as the number of prosumers grows

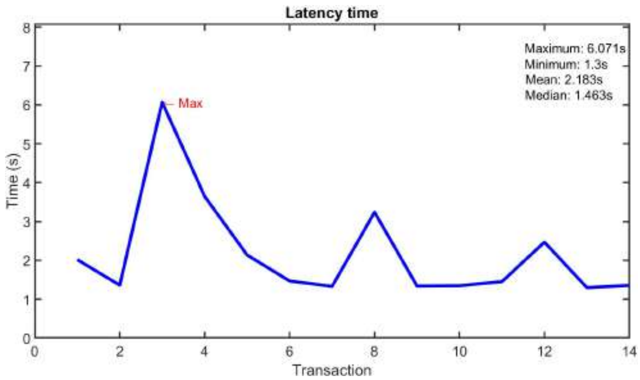

FIGURE 5. Latency for the different transactions of the 4-node test.

since the number of signatures is bound. For the worst-case scenario, the size of each transaction is 4 kB. Taking this into account, the number of prosumers participating in the system for a given storage capacity over a period of 20 years can be calculated. For instance, considering a memory of 1 TB, if a market round is performed every 5 minutes, the maximum number of prosumers is 107, whereas when market rounds are performed at 1-minute intervals, only 22 prosumers could participate.

In addition, some approaches have been adopted in which the BC size is reduced. Firstly, increasing the number of transactions inside a block, at the expense of increasing latency, result in a 20 % decrease of size (from 4 kB to 3,2 kB per transaction). Secondly, the number of market rounds that are carried out during the day can also be reduced using the proposed event-based strategy.

5) LATENCY

Different latencies can be considered. In this work, the latency refers to the waiting time that elapses between the execution of the transaction requested by the client application and the reception of the notification generated as a result of the request. This latency depends on the block creation time, which in the Hyperledger Fabric framework is set to 2 seconds by default. However, this value can be adjusted to the specific BC application being implemented. For the tests, the block creation time has been set to 1 second.

TABLE 3 shows the latency as a function of the number of nodes. The latencies were obtained by carrying out tests based on a single transaction at 5-minute intervals over one hour. Both the minimum and the median latency increase as the number of nodes grows. Furthermore, peak values of latency, above the usual range, occasionally appear (see FIGURE 5).

TABLE 4 depicts the latencies for the scenario in which every prosumer submits a transaction at the same time. It can be observed a decrease in the minimum and median latencies whereas the maximum latency taken up by a transaction is increased.

VI. EXPERIMENTAL RESULTS

As a use case, a MG connected to the main network, is emulated. To replicate real residential consumption and PV energy production profiles, real data obtained from [39] is used. In addition, electricity prices of the Spanish electricity market, published by Red Eléctrica de España in the ESIOS portal [40] on a daily basis are also used. For the use case considered in this paper, the operation of the MG in island mode is not addressed. Therefore, the MG is always connected to the main grid. Moreover, since the use case is representing residential users, reactive energy billing is not taking into account.

TABLE 3. Time delay for a single transaction.

Number of nodes	Minimum (s)	Maximum (s)	Median (s)
3	1,294	19,19	1,43
4	1,30	6,07	1,46
8	1,54	23,64	2,94
16	2,08	30,50	5,40

TABLE 4. Delay time taken to carry out several transactions simultaneously.

Number of nodes	Minimum (s)	Maximum (s)	Median (s)
3	1,223	22,76	1,30
4	0,95	12,54	1,00
8	0,70	25,22	1,83
16	1,38	34,97	5,92

The proposed MG comprises 18 heterogeneous prosumers, each one implemented in a Raspberry Pi 4 model B [33] as described in Section V. The 18 prosumers are categorized into three groups: (a) the first group is made up of 6 prosumers (1-6) with PV power generation and controllable and non-controllable loads; (b) the second group consists of 6 prosumers (7-12) with controllable and non-controllable loads, but no power generation capacity; and (c) the last group is composed of 6 prosumers (13-18) with only non-controllable loads. The details of each prosumer are described in TABLE 5.

The controllable loads, depicted in TABLE 5, are electric water heaters, one for each prosumer within the first and second group, i.e. prosumers from 1 to 12. Each heater has a rated power of 1.5 kW and a capacity of 3.6 kWh. It is assumed that these heaters have to be fully charged during the day to be completely emptied at the end of the day, emulating typical residential use. With this simple scenario, it is demonstrated how the BC-IEC 61850 proposal manages to improve the energy efficiency and the economic benefit of all prosumers.

For the study, a sunny day and a partially cloudy day are considered. A case of a very overcast day is not included because in that case there would hardly be any transactions

TABLE 5. Installed PV power and controllable loads of each prosumer in the use case scenario.

Prosumer	Installed PV (kW)	Heater	
		Power (kW)	Capacity (kWh)
1	3.75	1.5	3.6
2	2.5	1.5	3.6
3	1.75	1.5	3.6
4	1.25	1.5	3.6
5	4	1.5	3.6
6	1.5	1.5	3.6
7-12	---	1.5	3.6
13-18	---	---	---

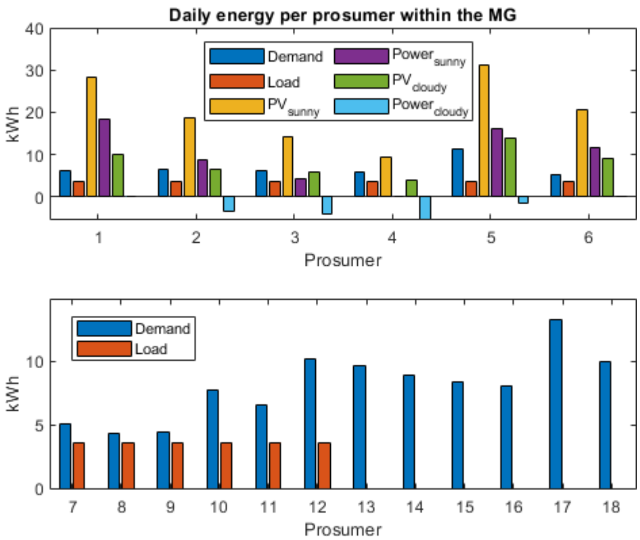

FIGURE 6. Spanish electricity market prices on a working day.

between the prosumers since the prosumer surplus of PV energy would be non-existent or very scarce.

FIGURE 6 illustrates the non-controllable and controllable load consumption of each prosumer per day, as well as the PV energy generated on the selected sunny and cloudy day. Additionally, the energy balance for each prosumer is shown for the two selected days. In both scenarios, the same profile of electricity consumption of non-controllable loads and the same profile of buying and selling grid prices are considered in order to make a more accurate comparison between both. In the case of PV generation, only the first 6 prosumers are displayed, as they are the only ones with installed PV power.

The electricity prices used in this use case are shown in FIGURE 7. As mentioned before, they are real prices from the Spanish electricity market [40] for a working day. It should be noted that in this market, it is possible to choose between a default billing or two period tariff, both are studied to validate the proposal.

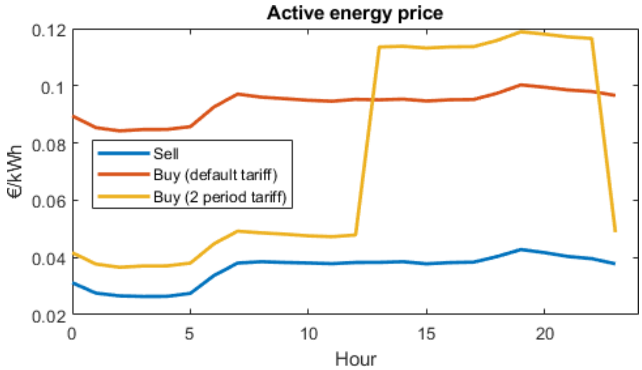

FIGURE 7. Energy consumed and generated by each prosumer on the sunny and the cloudy day under study.

Analysing the graph, the great difference in price between buying and selling energy to the grid is appreciated, which strengthens the justification of our market strategy. This is particularly noticeable during the peak period, from 13 to 23 hours, when the average price for selling energy to the grid is 0.039 €/kWh, and the buying price is 0.095 €/kWh for the default tariff and 0.113 euros/kWh for two period tariff.

A. TRANSACTION ANALYSIS

To evaluate the market update strategy, the sunny day profile data presented in FIGURE 7 is used. The study compares two different Thresholds for the SoD technique (1). The parameters to be evaluated are the number of updates made in the aperiodic market and therefore stored in the BC register and the energy estimation error committed by prosumer ($\text{Error}_i\,(t)$) and the total error in the MG ($\text{Error}_{MG}\,(t)$), evaluated by the following expressions:

$$\text{Error}_i\,(t) = \int_{t_{i,k-1}}^{t} Energy_i\,(t) - Energy_i(t_{i,k-1})dt \quad (12)$$

$$Error_{MG}\,(t) = \sum\nolimits_{i=1}^{N} Error_i(t), \quad (13)$$

This error integrates the difference between the last energy consumption per minute that was sent to the MG and the consumptions that have actually occurred during the time the market has not been updated. In this way it is possible to quantify the error made between the amount of energy estimated in that time interval and that which has actually been delivered. TABLE 6 quantifies the results obtained after emulating the proposed strategy for the sunny day under study.

Instead of presenting all the individual results of the different prosumers, for space consideration, their statistical data is shown. The mean and standard deviation (SD) of the 18 prosumers are calculated. In addition, the total result of the MG is presented, being this the most significant information. The table details both the number of market updates and the error made in the energy estimate throughout the day. Comparing $\Delta_{SoD} = 0.025$ with SoD with $\Delta_{SoD} = 0.005$, shows that

TABLE 6. Number of event-based updates and power error rate in blockchain registration on a sunny day.

Aperiodic threshold SoD (kWh)		Mean per Prosumer	SD per Prosumer	MG
0.005	Updates	30.222	49.584	**399**
	Error (kWh)	0.050	0.063	**-0.424**
0.025	Updates	2.167	4.731	**39**
	Error (kWh)	0.533	0.408	**-8.1188**

the number of updates is significantly lower, but the error is higher. This allows the designer to set a trade-off between the number of updates and the desired performance, always keeping the punctual error limited with threshold (Δ_{SoD}).

B. HARDWARE DIMENSIONING

Based on the data obtained through the implementation of the BC-IEC 61850 strategy in the test bench described in Section V, it is possible to estimate the resources that are necessary to implement the strategy in the use case.

The selected device to implement the developed system is a 64-bit ARM processor with a Linux-based operating system. Based on the previous study carried out in Section V, the SBC used easily meets the computing power requirements for this use case.

Regarding the bandwidth, each prosumer needs a minimum of 1 MB/s. If a user had speed problems, he could operate without an orderer on his computer, which would significantly reduce the amount of bandwidth needed, with a 0.5 MB/s connection being enough to meet requirements.

The most critical point in the implementation of the BC in a system that is expected to work over a long period of time is the amount of storage required, since having an always growing and distributed database in all the nodes of the network can be a challenge, but thanks to the proposed event-based technique (1), this BC could be working for a great number of years.

In TABLE 7, it can be seen that depending on the threshold (Δ_{SoD}) used, a different number of daily transactions are made, and this has a direct impact on the number of years that the BC can be in operation. It presents a trade-off between the precision of the technique employed and the time it will be possible to keep the system functioning. In order to calculate this time, the worst-case scenario, i.e. maximum storage capacity required per update, is taken into account. For each update (9), each transaction requires 4 KB (section V-C-4).

From the table, the significance of the reduction in the number of updates is appreciated, and a comparison is made with the one-minute periodic implementation due to it is the minimum time step of the proposed event-based implementation. In addition, sporadic maximum latencies of up to 34 seconds have been observed during testing, so it is reasonable to set a minimum time between transactions of one minute. The proposed system is able to reduce the amount of information to be stored in the BC register database by a factor of 18, committing an error of less than 0.5 kWh per day in the entire MG. Even in the worst-case scenario, the most accurate event-based technique indicates that a 64 GB storage system is suitable for the MG with 18 prosumers and it could reliably operate for at least 33 years.

TABLE 7. Comparison of storage capacity requirements according to the technique used.

Technique	Tx per day	Size per day (MB)	Size per year (GB)	Years microSD 64 GB
T = 1 min	31680	123,75	44,1	1,45
SoD (0,005)	1596	5,46	1,94	33
SoD (0,025)	156	0,53	0,19	336

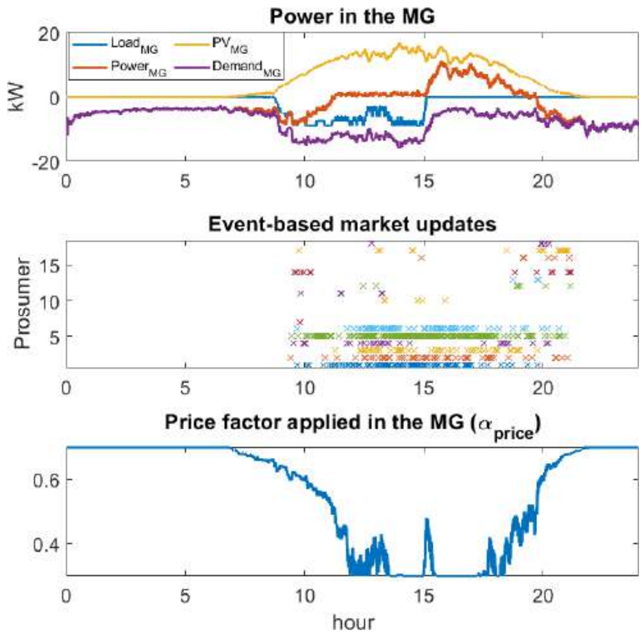

FIGURE 8. Sunny day use case: MG power profile throughout the day, updates of each prosumer and the price factor applied at each moment of the day.

C. USE CASE RESULTS

Finally, the results obtained for two types of days with the selected threshold ($\Delta_{SoD} = 0.005$ kWh) are presented. The energy profiles are those presented in FIGURE 6 and the prices are obtained from FIGURE 7.

In the first instance, FIGURE 8 shows the results for the sunny day. The graph shows the MG power profile throughout the day, the updates of each prosumer obtained from (1) and the price factor applied at each moment of the day (α_{price}) obtained from (6).

In the upper graph, the total power within the MG is shown. These power values are calculated as the sum of the PV power produced at each moment by each prosumer, in yellow; the sum of all the loads of each prosumer at each moment,

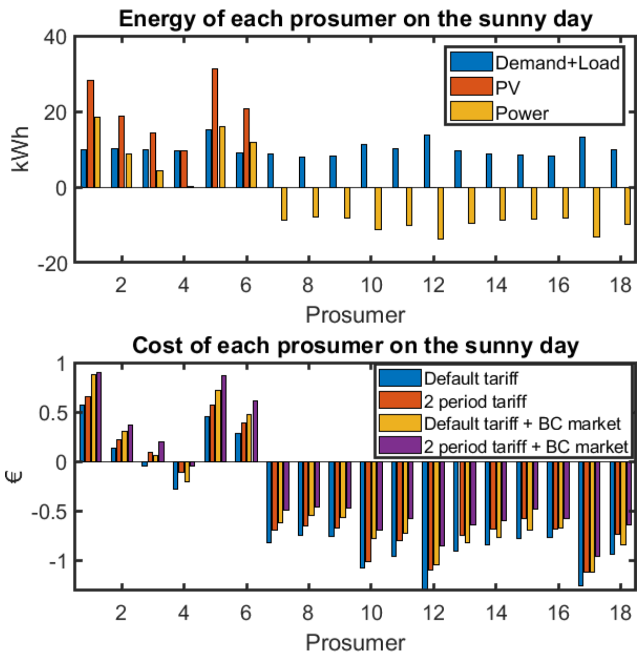

FIGURE 9. Sunny day use case: Economic study.

in purple; the sum of the controllable loads, in blue; and the power balance in the MG resulting from the difference in the generated energy minus the energy consumed, in orange. Analysing this graph, it can be seen how the production of the PV systems takes place between 7 and 21 hours. In the first hours the generation is low, so the energy is consumed locally by each prosumer, therefore no market event takes place. From 9 hours on, there are prosumers who begin to have surpluses, which activates the market. In the following hours, all surplus energy is absorbed by the controllable loads of the different prosumers. This can be seen in the energy balance signal around zero until approximately 17 hours. From that moment on, all the water heaters are fully charged, which means that the energy demand decreases sharply and a positive energy balance starts to be achieved in the MG. This surplus energy is sold to the grid.

The intermediate graph presents the moments of market activation and the prosumer that activates them. As commented previously, these events occur between 9 and 21 hours because these are the moments in which some prosumer has a surplus of PV energy. The number of events generated by each prosumer depends on the amount of variation in their energy balance over time, the total events in the MG are 399.

Finally, at the bottom graph, the price factor is shown for each instant of time. As expected, this factor is higher in the initial and final hours of the day because these are the moments when a smaller amount of surplus PV energy is available.

FIGURE 9 shows the economic study of the proposal applying the strategy described in section IV-C. The upper graph represents the amount of PV energy produced by each prosumer, in orange, the amount energy consumed, in blue, and the energy balance, in yellow, for the entire day. The

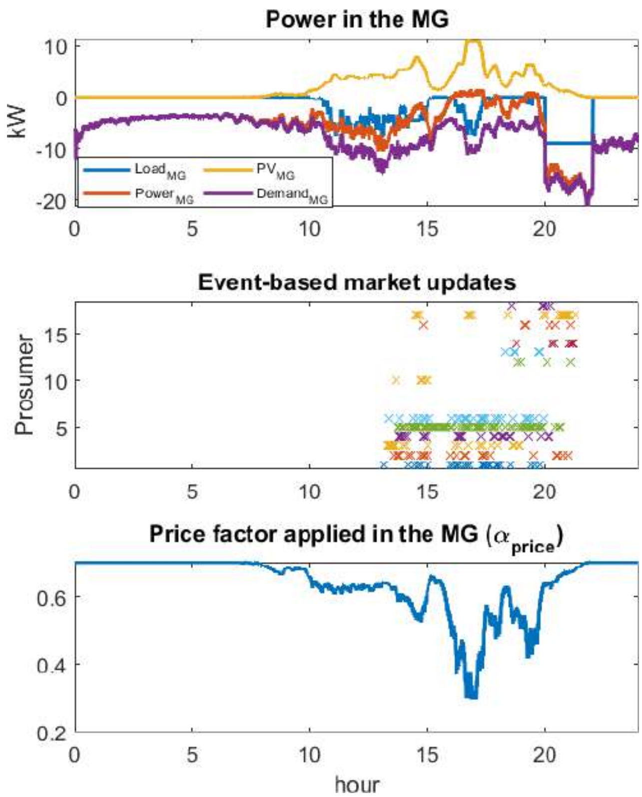

FIGURE 10. Cloudy day use case: MG power profile throughout the day, updates of each prosumer and the price factor applied at each moment of the day.

lower graph depicts the profit obtained (positive gain/negative loss) by each prosumer in four different scenarios:: (a) without the developed strategy for the default tariff; (b) without the developed strategy for the two period tariff; (c) with the MG strategy for the default tariff; and (d) with the MG strategy for the two period tariff. In the graph, it can be seen how significant the increase in profit of the energy producers is, as well as the savings of those who only consume, both for the two period tariff and the default tariff. The total energy balance of the MG is -58.52 kWh. The total cost of the MG, calculated as the sum of the individual costs of all prosumers, when the strategy is not applied is 10.03€ and 7.62€ for the default tariff and for the two period tariff, respectively. However, when the strategy is applied these total costs are reduced to 6.95€ and 4.52€ respectively. Therefore, for a sunny day, the proposed strategy achieves a significant saving in costs of 30,75% and 40% for the default tariff and for the two period tariff, respectively.

In the second instance, FIGURE 10 shows the results for the cloudy day. As in the previous case, it presents the MG power profile throughout the day, the updates of each prosumer and the price factor applied at each moment of the day. In this case, it can be seen that the surplus PV energy of the prosumers is more limited, so all the surplus produced is absorbed by the MG, for this reason the energy balance in MG is almost always below zero. Since not all the heaters can be fully charged with excess energy after 20 hours, the remaining

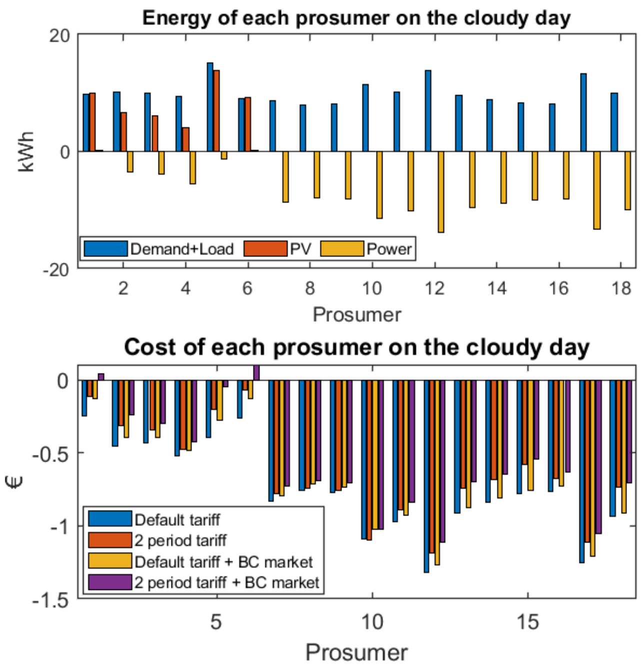

FIGURE 11. **Cloudy day use case: Economic study.**

capacity is charged with energy from the grid. This results in the peak consumption from 20 to 22 hours. The shortage of surplus of PV energy compared with the sunny day also justifies: the lower number of market activation events and the fact that the price factor of MG energy is almost always above 0.5 as it is a case where energy is more expensive due to lower PV production. The number of events and the error ($Error_{MG}$), calculated with (13), for an entire day in the MG are 235 and -0.6092 kWh respectively.

FIGURE 11 shows the economic study for the case of the cloudy day. In this case, the benefits produced are less than those of the sunny day because fewer transactions can be made. However, it is worth highlighting that despite having less surplus of energy available, all prosumers achieve a small economic benefit. Analysing the results achieved on a cloudy day, the balance of energy of the MG is -132,01 kWh. The total cost of the MG, calculated as the sum of the individual costs of all prosumers, when the strategy is not applied is 13,53€ and 11,52€ for the default tariff and for the two period tariff, respectively. However, when the strategy is applied these total costs are reduced to 12,55€ and 10.23€ respectively. Therefore, for a cloudy day, the proposed strategy achieves a significant saving in costs of 7,22% and 11,22% for the default tariff and for the two period tariff, respectively.

VII. CONCLUSION AND FUTURE WORK

This paper addresses one of the main technical challenges of the energy sector on account of the increasing number of DERs mainly based on renewable energy: the shift from a centralized operational approach to a distributed generation paradigm. This has encouraged the advent of MGs to propose new business models and management strategies. Within this context, this paper introduces an efficient management strategy, which is aimed at obtaining a fair division of costs billed by the utilities, without relying on a centralized utility or MG aggregator. The management strategy relies on the design of a local event-based energy market within the MG. This local market is based on the integration of the IEC 61850 standard into BC Smart Contracts, which facilitates the distributed communication among the commercial devices complying with the standard. The approach is implemented using low cost off-the-shelf hardware, such as the Raspberry Pi 4 model B platform, which reduces the time for the return on the investment. Consequently, the proposed strategy becomes an economically feasible solution for residential environments. The development of an event-based market also results in a reduction in the amount of computation and communication resources required, and more importantly, without negatively affecting the system performance. In addition, the proposed pricing strategy provides a win-win energy price for both energy producers and consumers, taking advantage of the gap between the price paid for the electricity consumed and that generated and injected to the grid. In the use case scenario, it is demonstrated that the proposed system is able to reduce the amount of information to be stored in the BC register database by a factor of 18. Furthermore, the error introduced is less than 0.5 kWh per day and for the entire MG. Finally, the strategy allows to achieve energy price savings up to 40%.

Future work will address the design of an islanded strategy, supported by batteries installed within the prosumers and the implementation of the BC-IEC 61850 in a real MG.

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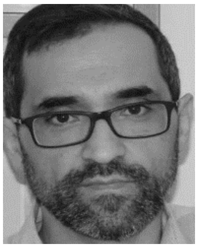

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